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# TRITIUM METHOD OIL CONSUMPTION AND ITS RELATION TO OIL FILM THICKNESSES IN A PRODUCTION DIESEL ENGINE

by


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## ABSTRACT

Oil consumption was measured in a modern production diesel engine using tritium as a radiotracer. The measurements were made primarily at two speeds and one load using first a single-grade lubricant and then a multi-grade lubricant.

These values were then compared to oil flow rates up/down the liner which were based on film thickness traces of a sister engine under the same loads and speeds. The traces were obtained using the laser-fluorescence technique. For the most part, it was discovered that there does not seem to exist a correlation between these flow rates and oil consumption. However, the traces do reveal that the crown land is dry on all four strokes and thus does not contribute to the engine's oil consumption.

A larger data base is necessary in order to accurately compare oil consumption to the film traces. This is currently in progress as of this writing.

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Procedures for the tritium method were supplied by the Sealed Power Corporation. They assisted greatly in getting the experiment off the ground.

The love and support that I got from my family was very important. They kept me going over the two years and, as always, were there when I needed them.

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# CHAPTER 1 BACKGROUND AND INTRODUCTION

Due to the EPA particulate emission standards for 1991 and 1994, it has become necessary to learn more about oil consumption and the driving forces behind it. Subsequently, an accurate determination of these driving forces could lead to designs of pistons, rings, and lubricants which improve both oil consumption and particulate emission.

This paper, then, has two purposes. First, initiate an industry proven method for measuring oil consumption, and second, compare these values to the average oil flow rates up the liner of a sister engine operating at the same loads and speeds. The oil consumption measurement technique, along with engine set-up and experimental procedures, will be explained further. The oil flow rates, however, have been calculated from oil film thickness data taken from, and explained in separate papers [1,2 respectively].

# CHAPTER 2 DESCRIPTION OF MEASURING TECHNIQUE

The technique used is a radiotracer method which uses tritium as its radiotracer. This method has been widely used for assessing oil consumption for over two decades. The method is fast, accurate, and economical relative to non-radioactive methods. This overall practicality and effectiveness is a major result of the advances of liquid scintillation counting.

## 2.1 BASIC METHOD

The following is a brief description of the basic method while a more detailed description of the general technique is found in Reference [3]. However, for ease of reference, the derivation of the oil consumption calculation equation, upon which this method is based, is included as Appendix A.

The basic procedure consists of running an engine with *radioactive lubricating oil* with a known radioactive level of disintegrations per minute (dpm). The total amount of hydrogen passing through the engine, via fuel flow and air flow, is measured and calculated. Through combustion, this hydrogen, along with the hydrogen/tritium from the oil, leads to the formation of water. A sample of this water is collected by condensing a sample of the exhaust gas. (Only a sample is needed since total measurements of the flow rates into the engine are obtained) Subsequently, the radiation concentrations of both the condensed water and the oil are determined using a liquid scintillation counter. These values are then applied to the oil consumption equation to arrive at the engine's total oil consumption.

## 2.2 SOOT SAMPLE COLLECTION

As seen in Appendix A, the general technique is based on complete combustion of the exhaust sample. For this paper, however, the exhaust sample is filtered and then

condensed instead of being completely combusted and then condensed. This results in an activity concentration (dpm/ml) of the condensed water and a total activity (dpm) of the soot sample.

In order for this method to be valid, two assumptions are made. First, the soot collected, if burned, would produce a negligible amount of water. Secondly, all of the water vapor in the sample is being condensed. This latter assumption is necessary since the consumption calculation requires radioactive *concentrations* vice total activities. Therefore, the soot sample total activity is divided by the amount of water collected and then added to the activity concentration of the water sample. A more in depth description of the procedures is included in Appendix E.

## 2.3 LIQUID SCINTILLATION COUNTING [4]

All radioactive levels are determined by a method known as liquid scintillation counting. This technique is highly sensitive and greatly responsible for the increased use of weak beta emitters such as carbon-14 and tritium. The basic technique, as with other methods of measuring radioactivity, relies on the interaction of nuclear radiation with matter. In this case, a luminescent material, or *scintillator*, is excited by radioactive disintegrations.

A scintillator, also referred to as either a phosphor or sometimes a fluor, is defined as a material which emits a brief pulse of fluorescent light when interacting with a high-energy particle or quantum. Therefore, the radioactive samples used in this experiment are mixed with a scintillator. The subsequent flashes of light, or *scintillations*, are detected by the counter by use of a photomultiplier. This in turn, over a set period of time, allows for the determination of the average disintegrations per minute (dpm) of each sample.

# CHAPTER 3 EQUIPMENT AND SET-UP

## 3.1 ENGINE

The engine used in this experiment is the KUBOTA EA300N, a single cylinder,4-stroke, IDI diesel. This engine is used primarily for remote power generation. A detailed description of the engine's geometry and performance is included in Appendix B.

This engine was chosen only because the film thickness measurements used in this paper were obtained from an engine of the same make and model [1].

## 3.2 RADIOACTIVE LUBRICATING OILS

Radioactive oil for these experiments is purchased commercially. The oil received has been through a tritiation process which results in approximately 250 mCu in one ml of oil. Subsequently, this oil is divided up and thoroughly mixed with Pennzoil SAE-30 (single-grade) and Pennzoil 15W-40 (multi-grade). The tritiation process is explained further in Appendix B.

These oils are used primarily for the same reason as above for the engine. In addition, they should provide a good comparison of single- and multi-grade oils since the only difference is the addition of a polymer VI improver to the 15W-40.[3]

## 3.3 ENGINE INSTRUMENTATION

The engine is fitted with thermocouples in order to monitor operating temperatures (Fig. 1). The thermocouples measure the inlet air temperature, the coolant temperature, the oil sump temperature, the exhaust temperature, and the liner temperatures. The latter thermocouples coincide with the top ring at TDC, mid-stroke, and BDC. A laminar air flow element is also used to measure the air flow while a burette system is used to measure the volume flow rate of the fuel. A more detailed listing of the measuring equipment is included in Appendix B.

## 3.4 DESCRIPTION OF PISTON AND RINGS [2]

The piston and rings (Fig. 2) are representative of modern engine design. The piston is made of aluminum and accommodate three piston rings. It has round lands and a barrel shaped skirt. Behind and below the oil control ring, there are oil flow relief holes that allow the circulation of oil up the piston skirt on the liner side and back down to the sump inside the piston.

The three piston rings consist of a top ring, a scraper ring, and an oil control ring. The top ring is a half-keystone design with a 7° keystone angle. It is made out of cast iron with a chromium strip embedded into its face to improve wear resistance. The resulting face profile is asymmetric. The scraper ring has a tapered face and an undercut on its face side to provide the correct tilt angle when compressed to its working diameter. It is also made of cast iron. The oil control ring is a one piece type made of cast iron also, and, like the top ring, its rails have a chromium strip embedded into them. The oil control ring also has slots between the rails to allow the flow of oil through the ring to the holes in the piston mentioned above.

## 3.5 SAMPLING SYSTEM

Figure 3 is a schematic of the sampling system in use. As shown, the sampling system is connected to an exhaust tank. This tank is used to help eliminate the exhaust pulse that exists when operating a single cylinder engine. This entire system, consisting of inexpensive components, is placed on a small lab cart which allows for portability and for an easy connection to a different engine.

## 3.6 OIL FILM THICKNESS MEASUREMENTS

The film thickness traces referred to are obtained from reference [1] which uses a laser-fluorescence technique. This basic technique consists of mixing the lubricant with a fluorescent dye and then, during operation, focusing a HeCd (blue) laser through a quartz window installed in the liner. The resulting fluoresced (green) light is then collected and converted to a voltage signal using a photomultiplier [2]. Lastly, the voltage signal is converted into microns using a calibration coeffecient (unique for each trace). This coeffecient is based on the voltage readings obtained when etch marks of known depths on the piston skirt pass the quartz window.[1]

More in depth descriptions of this technique can be found in references [1] and [2].

# CHAPTER 4 DESCRIPTION OF EXPERIMENTS

## 4.1 PROCEDURES

At each given load and speed, the engine is allowed to stabilize. Subsequently, flow rates are measured and samples are taken in accordance with the step-by-step procedures in Appendix C. The samples are then prepared in accordance with Appendix D in order for the scintillation counter to be effective.

Following sample preparation, the samples are placed in the scintillation counter to determine their individual radioactive levels. These values, along with the measured flow rates, are then used to calculate oil consumption. Actual formulas and an example of the spreadsheets in use are included in Appendix E.

After collecting data using the first oil, the engine is flushed to minimize contamination of the next test oil. A flow chart of these basic procedures is illustrated in figure 4.

## 4.2 ENGINE OPERATING CONDITIONS

The primary loading conditions for each oil consisted of full load at 1500 rpm and full load at 3000 rpm (approximately 9.5 ft-lbs for each). As before, these conditions were used in order to duplicate the conditions under which the film thickness data was taken. Secondary loading conditions consisted of 2000 rpm and 2500 rpm at the same torque. These latter conditions were used mainly for graphic continuity between low and high speeds.

# CHAPTER 5 GRAPHIC RESULTS

## 5.1 OIL CONSUMPTION MEASUREMENTS

Oil consumption measurements for the desired load and speeds using Pennzoil's SAE-30 and 15W-40 are illustrated in figures 5 and 6, respectively. Figure 7 is then an overlay of the previous two graphs with figure 8 being another comparison but in the form of a bar chart.

The volatility of a new oil (SAE-30) is also examined. The results, included as figure 9, illustrate how oil consumption rates decrease and then stabilize with time (for a constant load and speed). Volatility information is desirable since the film thicknesses were obtained from the sister Kubota using new lubricating oils.

## 5.2 OIL FILM THICKNESSES

Figures 10, 11, 12, and 13 illustrate a subset of the average film thickness traces for ten compression, expansion, exhaust, and intake strokes, respectively [1]. For these traces, the engine was using SAE-30 and was running at full load at 1500 rpm. The traces for 3000 rpm and for the different oil are similar to these and are therefore not included. Interpretation of this data, which can be confusing to the first-time observer, is described in length in reference [2].

# CHAPTER 6 ANALYSIS AND DISCUSSION

## 6.1 HYPOTHESES

There exists three prevalent hypotheses on lubricating oil consumption, two of which deal with oil being drawn in and around the top ring at or near the end of the expansion stroke. At this point, the high pressure below the top ring forces the oil around the top ring where it either (1) accumulates on the crown land from where it is later burned off or (2) is "blown" up into the combustion chamber and consumed. The third hypothesis is based on oil being transported by the top ring face. Subsequently, some of this oil is deposited onto the liner at or near top ring reversal (TRR) where it is later consumed.

For each hypothesis, there exists a corresponding volume. These volumes are calculated by first finding their respective areas which are illustrated in figure 14. The areas are then swept around the circumference of the bore to determine the volumes. Table 1 lists the areas and the volumes calculated.

| SPACE | AREA ($mm^2$) | VOLUME ($mm^3$) |
|---|---|---|
| A) Crown land crevice | 1.33 | 313.0 |
| B) Ring/groove crevice (top and bottom) | 0.3 | 70.7 |
| C) Ring/groove crevice (backside of ring) | 1.02 | 241.0 |
| D) Between ring and liner | .00386 | 0.91 |

Table 1. Areas/Volumes of possible oil consumption mechanisms

These volumes can in turn be related to an oil flow rate, in g/hr, based on engine operating speed and oil density (Refer back to Appendix E). Unfortunately, volumes A, B, and C above result in rates on the order of thousands of grams per hour with volume D being on the order of 50 grams per hour. These values are extraordinarily high and do not scale with oil consumption (figures 5 and 6). Thus they cannot offer much guidance in determining oil consumption mechanisms. Actual volumes necessary to resemble the oil consumption values are on the order of 0.01% of volumes A and C, 0.05% of volume B, and just 3.0% of volume D.

## 6.2 ANALYSIS AND DISCUSSION

As discussed in Chapter 5 of reference [2], the film thickness data does not usually allow for a determination of where the oil lies (i.e. on the piston, on the liner, or on both). However, as figures 10 through 13 illustrate, the oil film thickness before the piston arrives (-4mm to 0mm for the upstrokes) is relatively *the same* as when the crown land is passing (0mm to 9.5mm for the upstrokes). Therefore, it is apparent that the piston crown land is virtually oil free and thus, does not contribute to oil consumption. It is important to mention that this film trace characteristic is also shared by the other traces for the higher speed and with the different oil.

Based on the above line of reasoning, the first hypothesis can be easily refuted. The second one, however, can neither be directly refuted nor explicitly proved by this method of film measurement. This is because the hypothesis addresses oil which enters the combustion chamber by way of neither the piston nor the liner. However, further data analysis of the film traces does allow for some broad conclusions to be made concerning both this and the final hypothesis.

This subsequent data analysis first requires the use of existing computer programs which have been modified for the Kubota engine [5]. These programs calculate the volume differences ($mm^3$/cycle) of various crank angle regions for both the power and the gas

exchange strokes. Only five regions, which are listed below in Table 2, are analyzed in this paper. The methods and reasons for computing these particular regions, along with copies of the programs, are included in Appendix F.

| REGION | PISTON AREA |
|---|---|
| I | Crown land |
| II | Top Ring |
| III | 1 ring width below top ring |
| IV | Second Land |
| V | Second (Scraper) Ring |

Table 2. Piston Regions of Film Thickness

The title of each region in the table explains which part of the piston is passing the quartz window at that instant. In addition, the regions are labeled on an expanded version of the aforementioned compression stroke. (Figures 15 and 16)

Secondly, in order to compare a regions volume difference to the measured oil consumption, the former is converted to an oil flow rate up (or down) the liner in g/hr. This is done based on the volume difference, the speed, and the oil's density. (Refer back to Appendix E for calculations)

Tables 3 and 4 and Tables 5 and 6 tabulate the data collected using SAE-30 and 15W-40, respectively. A positive value indicates that the upstroke volume is greater than the downstroke and vice versa. Subsequently, figures 17 through 22 are included to illustrate these various flow rates of the two oils for the different speeds. On each figure, the respective oil consumption is included in order to make relative comparisons.

| SAE-30 at 1500rpm | | PWR EXCHANGE | | GAS EXCHANGE | | TOTAL (pwr+gas) | |
|---|---|---|---|---|---|---|---|
| | | Vol Diff | Oil Flow | Vol Diff | Oil Flow | Vol Diff | Oil Flow |
| Region | I | 0.04 | 1.51 | 0.00 | 0.00 | 0.04 | 1.51 |
| Region | II | 0.01 | 0.38 | -0.08 | -3.03 | -0.07 | -2.65 |
| Region | III | 1.11 | 42.01 | -0.23 | -8.70 | 0.88 | 33.30 |
| Region | IV | 2.30 | 87.04 | -0.52 | -19.68 | 1.78 | 67.36 |
| Region | V | -0.02 | -0.64 | -0.11 | -4.16 | -0.13 | -4.81 |

Table 3. Oil Flow Rates up the Liner (SAE-30 at 1500 rpm)

| SAE-30 at 3000rpm | | PWR EXCHANGE | | GAS EXCHANGE | | TOTAL (pwr+gas) | |
|---|---|---|---|---|---|---|---|
| | | Vol Diff | Oil Flow | Vol Diff | Oil Flow | Vol Diff | Oil Flow |
| Region | I | -0.34 | -12.87 | -0.12 | -4.54 | -0.46 | -17.41 |
| Region | II | 0.08 | 3.03 | -0.21 | -7.95 | -0.13 | -4.92 |
| Region | III | 0.74 | 28.01 | -0.23 | -8.7 | 0.51 | 19.3 |
| Region | IV | 1.43 | 54.12 | -0.45 | -17.03 | 0.98 | 37.09 |
| Region | V | 0.32 | 12.11 | -0.19 | -7.19 | 0.13 | 4.92 |

Table 4 Oil Flow Rates up the Liner (SAE-30 at 3000 rpm)

| 15W-40 at 1500rpm | | PWR EXCHANGE | | GAS EXCHANGE | | TOTAL (pwr+gas) | |
|---|---|---|---|---|---|---|---|
| | | Vol Diff | Oil Flow | Vol Diff | Oil Flow | Vol Diff | Oil Flow |
| Region | I | -0.04 | -1.51 | 0.08 | 3.03 | 0.04 | 1.51 |
| Region | II | 0.03 | 1.14 | -0.04 | -1.51 | -0.01 | -0.38 |
| Region | III | 0.63 | 23.84 | 0.05 | 1.89 | 0.68 | 25.73 |
| Region | IV | 1.17 | 44.28 | -0.08 | -3.03 | 1.09 | 41.25 |
| Region | V | 0.16 | 6.06 | -0.01 | -0.38 | 0.15 | 5.68 |

Table 5. Oil Flow Rates up the Liner (15W-40 at 1500 rpm)

| 15W-40 at 3000rpm | | PWR EXCHANGE | | GAS EXCHANGE | | TOTAL (pwr+gas) | |
|---|---|---|---|---|---|---|---|
| | | Vol Diff | Oil Flow | Vol Diff | Oil Flow | Vol Diff | Oil Flow |
| Region | I | -0.22 | -8.33 | -0.16 | -6.06 | -0.38 | -14.38 |
| Region | II | 0.10 | 3.78 | -0.20 | -7.57 | -0.10 | -3.78 |
| Region | III | 0.46 | 17.41 | -0.38 | -14.38 | 0.08 | 3.03 |
| Region | IV | 0.91 | 34.44 | -0.66 | -24.98 | 0.25 | 9.46 |
| Region | V | 0.09 | 3.41 | -0.35 | -13.25 | -0.26 | -9.84 |

Table 6. Oil Flow Rates up the Liner (15W-40 at 3000 rpm)

Upon examination of these figures, it is seen that a majority of the regions show absolutely no correlation to oil consumption. However, a slight correlation does exist for Region II, the top ring, but only during the power exchange strokes. Therefore, a closer look is taken at non-dimensionalized values for this case and for the oil consumption. This is accomplished by dividing each rate by its corresponding 1500

rpm value. (i.e. all of the 1500 rpm values will equal one) The results are illustrated in figure 23 for SAE-30 and figure 24 for 15W-40, however, it is seen that the oil flow rates do not duplicate the trends of the oil consumption in either case.

## 6.3 PROBABLE ERRORS IN ANALYSIS TECHNIQUE

When comparing oil flow rates to oil consumptions, if in fact film thickness in this case can even be related to oil consumption, only trends can be looked for. An exact matching of values would be virtually impossible for the following reasons:

a) Oil consumption measurements vary within an engine, therefore they will vary even more between separate, but identical, engines.

b) The oil film data is obtained while using new, and thus more volatile, lubricating oil. (Refer back to figure 9)

c) As previously mentioned, the calibration coefficients for each film trace are determined by way of etch marks on the skirt [1]. However, there may exist a temperature gradient between the skirt and the rings and lands. This gradient would result in different calibrations for these latter regions since the fluorescence of the oil is inversely proportional to its temperature [6].

d) The oil flow relief holes, described in sect.3.4, is probably what attributes to the absence of correlation between oil consumption and film thickness. Figure 25 illustrates that, over the length of the piston, the power strokes tend to have more oil on the way up then on the way down and vice versa for the gas exchange strokes. These results imply that:

1) after the oil control ring passes the window on the compression stroke and before it passes the window on the expansion stroke, oil is returned to the sump via the flow holes.

2) after the oil control ring passes the window on the exhaust stroke and before it passes the window on the intake stroke, oil is supplied to the sump via the flow holes.

## 6.4 MISCELLANEOUS ANALYSIS

The temperature of the upper portion of the liner during operation is plotted in figure 26 for the RPMs shown. These temperatures are then used to determine the high and low shear viscosities (figure 27) and the surface tension (figure 28) of the oils in use [7]. Lastly, the oil consumptions versus viscosities are plotted in figure 29. Unfortunately, no trends or relationships between the two are observed.

# CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

The primary conclusions and recommendations are as follows:

1) The crown land is virtually dry and therefore does not contribute to oil consumption.

2) The top ring is the only region whose oil film thickness characteristics remotely resemble oil consumption. However, before any conclusions can be formulated, more comparisons need to be made between this region's flow rate and oil consumption.

3) The concept of oil being "blown" around the top ring and into the combustion chamber is still a viable solution, however, the top ring region might be an additional driving force behind oil consumption.

4) The oil flow relief holes provide a significant unknown which might make this type of flow rate analysis for this particular set-up invalid. A recommended set-up would consist of obtaining film thickness measurements through a window placed such that the oil control ring never passes over it.

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# APPENDIX A DERIVATION OF OIL CONSUMPTION CALCULATION [3]

The following derivation is based on the composition of the combustion water. This water comes from the water in the inlet air and from its formation via the combustion process of the fuel and of the oil. If radioactive hydrogen is only in the oil, then:

$$\frac{\text{disintegrations per minute (dpm)}}{\text{Wt of sample of combustion } H_2O} = \frac{\text{Lube oil consumption dpm}}{H_2O \text{ from fuel comb.} + H_2O \text{ from oil comb.} + H_2O \text{ from air}} \quad \text{(a.1)}$$

The following symbols are used:

$R_o$ = Wt rate of oil consumption, g/hr

$R_f$ = Wt rate of fuel consumption, g/hr

$R_a$ = Wt rate of air consumption, g/hr

$K_o$ = Water formation constant of oil, g water formed/g oil burned

$K_f$ = Water formation constant of fuel, g water formed/g fuel burned

$h_s$ = Specific humidity, g $H_2O$/g air

$SA_{cw}$ = Specific Activity for $H_2O$ sample, dpm/g of sample

$SA_o$ = Specific Activity for lube oil, dpm/g

t = time, hr

These values, when substituted into equation. a.1, result in:

$$SA_{cw} = R_o t(SA_o)/[R_o t K_o + R_f t K_f + R_a t h_s]$$

Subsequent grouping of the $R_o$ terms results in:

$$R_o = [R_f K_f + R_a h_s]/[(SA_o/SA_{cw})-K_o]$$

The water formation constants, $K_o$ and $K_f$, are determined based on their hydrogen to carbon ratios (H/C). (See Appendix E)

The H/C ratios for the Pennzoil oils are obtained via Dr. Tayeb Benchaita of Pennzoil Products. The H/C for the fuel is based on a standard light diesel fuel. Actual values and sample calculations are included in Appendix E.

# APPENDIX B DETAILED EQUIPMENT DESCRIPTION

## B.1 KUBOTA EA300N CHARACTERISTICS

The Kubota EA300N's detailed geometry is presented in the following table.

| | |
|---|---|
| Make | Kubota |
| Model | EA300N |
| Type | Horizontal, 4-stroke, IDI Diesel |
| Number of cylinders | 1 (one) |
| Bore and Stroke | 75 x 70 mm (2.95 x 2.76 in.) |
| Displacement | 0.309 liters (18.86 cu. in. ) |
| Compression Ratio | 23:1 |
| Cooling System | Water cooled - natural convection |
| Lubrication System | Trochoidal pump (no oil filter) |
| Rated Brake Horsepower | 4.48 kW (6hp) @ 3000 RPM |
| Maximum Torque | 15.2 Nm (11.2 ft-lbf) |
| Typical Application | Remote Power Generation |

Table B.1 Engine Characteristics

A unique characteristic of this engine is that it does not have a paper filter. Instead, it has a strainer screen and a magnet to keep large pieces of debris and metal shavings from entering the oil pump. Unfortunately, this allows the dirt and grit that is introduced into the oil during operation to remain in the oil. Therefore, the engine oil becomes black very quickly. This "blackness" requires the oil samples to be diluted and centrifuged (see Appendix D) in order for the scintillation counting technique to be of use.

## B.2 RADIOACTIVE OIL [6]

The tritiated oil received has been through a reduction process using tritium gas. This gas, plus one ml of the neutral base oil, was mixed with forty mg of a platinum black catalyst and stirred overnight. Afterwards, any labiles were removed using 50% benzene methanol. The final result is the addition of tritium atoms to the hydrocarbon molecules in the oil. This process is referred to as either a hydrogenation or tritiation process.

## B.3 ENGINE INSTRUMENTATION

The following is a listing of the instrumentation used while collecting data for these experiments. (Refer back to Fig. 1)

| COMPONENT: | Make, Model #: |
|---|---|
| Liner Thermocouples (3) | Omega, J-type |
| Liner Thermocouple Readout | Omega, Model #2168A |
| Other Thermocouples | Omega, K-type |
| Thermocouple Readout | Omega, Model #199 |
| Hall-effect Speed Sensor | Minarik, Visi-Tach |
| Load Cell | Eaton, Model #3169 |
| Laminar Air Flow Element | Meriam Instr., Model 50MW20-2 |
| Liquid Scintillation Counter | Packard, 2000 CA TRI-CARB |

Table B.2 Measuring Equipment and Instrumentation

# APPENDIX C RADIOTRACER PROCEDURES

## C.1 MIXING AND "BREAKING-IN" THE OIL

Non-radioactive oil should be mixed with radioactive oil until the concentration level is approximately six microcuries per gram (6 $\mu$Cu/g). If a completely new batch of oil is used, the engine should be operated for around 5 hours before any data samples are collected. This break-in period allows any light ends to be burned off. (Refer back to figure 9)

## C.2 SAMPLING PROCESS

Before samples are taken, operate the engine continuously at the given load and speed to allow temperatures to stabilize. Between speed changes, allow approximately 15 minute for stabilization. After stabilization, run the vacuum pump for a short period of time in order to draw exhaust gas through the sampling system. This is done (1) to ensure that the engine and sampling system are making good water samples and (2) to ensure that any water residue from the last data run is emptied from the condenser coils. The following is a step-by-step description of the actual sampling process.

1) Replace water collection bottle with a clean one
2) Replace exhaust filter with a new one
3) Turn on the vacuum pump to initiate the sampling process
4) Measure and record the volume flow rate of fuel using the installed burette and a timer
5) Record the pressure difference across the laminar flow element using the installed inclined manometer
6) Record operating temperatures
7) After approximately ten minutes, secure from sampling by turning off the vacuum pump. This time limit allows for:

a) collection of a sufficient amount of condensed water and

b) a sufficient number of piston ring revolutions and thus a better average oil consumption

8) Remove both the filter and the water collecting bottle and replace with clean ones (see Appendix D for preparation)

9) Stabilize at the next load and speed and repeat from step 3 on.

10) After running at the desired load and speeds, secure the engine and drain approximately 50 ml of lubricating oil followed by draining one ml of oil into a separate test tube (see Appendix D for preparation)

11) Return the 50 ml of drained oil to the sump

12) Record the barometric pressure and relative humidity

All data is recorded on available data sheets in the units indicated on the sheet. Using these units allows the values to be inputted directly into the present spreadsheets (Appendix E). Copies of the data sheets in use are included as the next two pages.

## C.3 EXPERIMENTAL DATA SHEET

UNIFORM INPUT:

DATE -------------------

Oil brand --------------

Oil Activity -----------
*(dpm/.5 ml kero/oil soln)*

Barometric pressure ----
*(mm mercury)*

Air temperature --------
*(celsius)*

Humidity coeff. --------

Relative Humidity ------

UNIQUE INPUT:

| | |
|---|---|
| Load --------- *(lbs)* | Load --------- *(lbs)* |
| Speed -------- *(rpm)* | Speed -------- *(rpm)* |
| Fuel rate ---- *(ml/sec)* | Fuel rate ---- *(ml/sec)* |
| Air press. diff. across element - *(inches wtr)* | Air press. diff. across element - *(inches wtr)* |
| amount of water collected ---- *(ml)* | amount of water collected ---- *(ml)* |
| activ of soot sample ------- *(dpm)* | activ of soot sample ------- *(dpm)* |
| activ conc. of wtr sample --- *(dpm/ml) or (dpm/g)* | activ conc. of wtr sample --- *(dpm/ml) or (dpm/g)* |
| TEMPERATURES: | TEMPERATURES: |
| exhaust ------ | exhaust ------ |
| air inlet ---- | air inlet ---- |
| oil ---------- | oil ---------- |
| coolant ------ | coolant ------ |
| liner: | liner: |
| upper ---- | upper ---- |
| middle --- | middle --- |
| lower ---- | lower ---- |

# APPENDIX D SAMPLE PREPARATION [7]

## D.1 WATER SAMPLES

1) Filter the condensed water into a clean test tube
2) Add and mix a sufficient amount of ammonium hydroxide solution to the sample to bring the PH up to 7 (neutral). [7,8]
3) Centrifuge the sample for approximately ten minutes
4) Filter again if necessary
5) Pipette 10 ml of fluor solution into a counting bottle
6) Pipette 1 ml of the water sample into the counting bottle (note - more or less water may be counted but the spreadsheet is set up for 1 ml --see Appendix E)
7) Replace top, mix, and number the sample

## D.2 SOOT SAMPLES

1) Place the filter in a tube containing approximately 30 ml of fluor solution and shake vigorously to mix well
2) Allow two hours for the fluor solution to dissolve the soluble hydrocarbons and then shake again
3) Filter the solution into a clean test tube. Repeat if necessary
4) Pipette 10 ml of the fluor solution into three counting bottles each
5) Divide the filtered solution among the bottles
6) Replace the tops, mix, and number the samples

## D.3 OIL SAMPLES

1) Pipette 10 ml of kerosene into a clean test tube
2) Pipette .2 ml of the oil sample into the kerosene. Subsequently, flush

**the pipette with the oil/kerosene solution until all visible oil residue is removed from the pipette.** Place pipette into the solution

3) Mix well and centrifuge for approximately ten minutes

4) Pipette 10 ml of the fluor solution into a counting bottle

5) Pipette .5 ml of the oil/kerosene solution into the counting bottle (note - as before, more or less may be counted but the spreadsheet is set up for .5 ml -- see Appendix E)

6) Replace top, mix, and number the sample

All samples are taken to the Radiation Protection Office so that their activity levels may be counted using a liquid scintillation counter.

# APPENDIX E FORMULAS AND EXAMPLE CALCULATIONS

## E.1 OIL CONSUMPTION

### E.1a MEASURED CONSTANTS

$\rho_f$ = fuel density, g/ml = 0.838

$\rho_o$ = oil density, g/ml = 0.826 (15W-40) or 0.841 (SAE-30)

$(H/C)_f$ = hydrogen to carbon ratio of fuel = 1.8 (light diesel)

$(H/C)_o$ = hydrogen to carbon ratio of oil = 1.88 (15W-40) or 1.78 (SAE-30)

LFE = Laminar flow element rating, CFM/in water

### E.1b CALCULATED CONSTANTS

$K_f$ = water formation constant of fuel

$= [g\ H_2O/g\ H] \times [g\ H/\ g\ fuel]$

$= [(2 + 16)/2] \times [(H/C)_f/(12 + (H/C)_f)]$

$= 1.174$

$K_o$ = water formation constant of oil

$= 1.219$ (15W-40) or 1.163 (SAE-30)

### E.1c MEASURED VARIABLES

$V_f$ = volume flow rate of the fuel, ml/sec

dP = differential pressure across laminar air flow element, inches water

W = amount of water condensed, ml

$SA_{cw}'$ = specific activity of condensed water, dpm/ml

$A_s$ = total activity of soot sample

$SA_o'$ = specific activity of oil/kerosene mixture, dpm/(.5 ml of oil/kero solution)

atm = barometric pressure, mm of mercury

$T_a$ = air temperature, $^oC$

H = relative humidity, %

## E.1d CALCULATED VARIABLES

$h_s$ = specific humidity, g $H_2O$/g air

= determined from psychrometric chart using **H** and $\mathbf{T_a}$

$R_f$ = wt rate of fuel, g/sec

= $V_f \times \rho_f$

$\mu_c$ = viscosity coefficient

= $1 - [.0025714 \times (T_a - 20)]$ (note -- accurate for $15 < T_a < 35$)

$\rho_a$ = density of air, $g/m^3$

= (**atm**) x (133.32 Pa/mm Hg) x (28.962 g/mol) x (mol $^oK$/8.3143 Nm) x

[1/(273 + $T_a$)$^oK$] (note -- ideal gas law)

$R_a$ = wt rate of air, g/sec

= (**LFE**) x (**dP**) x (.02832 $m^3/ft^3$) x (min/60 sec) x [(**atm**)/29.92 in Hg] x

(in/25.4 mm) x {530 $^oR$/[460 + (1.8$T_a$ + 32)]$^oR$} x $\mu_c \times \rho_a$ [8]

$SA_{cw}$ = total specific activity of exhaust sample, dpm/g

= $SA_{cw}' + (A_s/W)$

$SA_o$ = total oil consumption, g/hr

= $[R_fK_f + R_ah_s]/[(SA_{cw}/SA_o) - K_o]$ x (3600 sec/hr)

## E.2 OIL FLOW RATES (FROM FILM THICKNESS TRACES)

RPM = revolutions per minute

$V_{op}$ = average oil volume difference, for a given region, between the

power exchange strokes, $mm^3$/cycle

= calculated using an existing computer program which was modified

for the Kubota (Appendix F)

$V_{og}$ = average oil volume difference, for a given region, between the gas exchange strokes, $mm^3$/cycle

= calculated using an existing computer program which was modified for the Kubota (Appendix F)

$V_o$ = total avg. volume difference between the up and down strokes, $mm^3$

$= V_{op} + V_{og}$

$R_{op}$ = rate of oil flow up the liner based on film thicknesses during the power exchange strokes, g/hr

$= (V_{op}) \times (cm^3/1000\ mm^3) \times (RPM) \times (60\ min/hr) \times (cycle/2\ revolutions) \times (\rho_o)$

$R_{og}$ = rate of oil flow up the liner based on film thicknesses during the gas exchange strokes, g/hr

$= (V_{og}) \times (cm^3/1000\ mm^3) \times (RPM) \times (60\ min/hr) \times (cycle/2\ revolutions) \times (\rho_o)$

$R_o'$= overall rate of oil flow up the liner based on film thicknesses, g/hr

$= R_{op} + R_{og}$

All of the preceding formulas are incorporated into LOTUS 123 v2.0 spreadsheets. Examples of these spreadsheets are included as the following six pages. The first two pages are for oil consumption calculations and the last four are for oil rates based on the film thickness data.

## E.3 LOTUS 123 v2.01 SPREADSHEETS

### OIL CONSUMPTION CALCULATIONS:

```
                                  UNIFORM
                                  ---------

        INPUT                                      CALCULATIONS

oil H/C ratio ---------      1.78  / Oil formation constant ---1.162554
(SAE-30 = 1.78)                    /
(15W-40 = 1.88)                    /
                                   /
fuel H/C ratio --------       1.8  / Fuel formation constant --1.173913
                                   /
activ of oil smpl -----     57052  / activ conc oil -----------6919505.
(dpm/.5 ml soln)                   / (dpm/g)
                                   /
oil density -----------     0.841  /
(SAE-30=.841)                      /
(15W-40=.826)                      /
                                   /
Barometric Pressure ---       777  /
(mm mercury)                       /
                                   /
humidity coeff --------      0.01  /
(lb wtr/lb air)                    /
                                   /
air temperature -------        28  /
(celsius)                          /
```

1 UNIQUE

| INPUT | | CALCULATIONS | |
|---|---|---|---|
| Load (lbs) ------------ | 7.6 | TOTAL oil consumption ---- (g/hr) | 1.425019 |
| Speed (rpm)------------ | 1500 | | |
| fuel rate ------------- (ml/sec) | 0.2038 | fuel rate ---------------- (g/sec) | 0.170734 |
| air pressure diff ----- (inches water) | 1.275 | air rate ----------------- (g/sec) | 3.529877 |
| | | equivalence ratio -------- (F/A)s = 0.0693 | 0.698160 |
| activ of soot smpl ---- (dpm/1 ml soln) | 632 | total activ of soot smpl - (dpm) | 632 |
| activ conc wtr smpl---- (dpm/ml) or (dpm/g) | 11376 | total conc. of sample ---- (dpm/ml) or (dpm/g) | 11593.93 |
| amount wtr collected -- (ml) | 2.9 | | |
| | | oil consump (burned) ----- | 1.398182 |
| | | oil consump (unburn) ----- | 0.026734 |
| | | Total ------------------- | 1.424916 |

OIL FLOWS UP THE LINER:

| SAE-30 | PISTON REGIONS | | AVG VOL PWR STRK (cu mm) | OIL FLOW PWR STRK (g/hr) | AVG VOL GS XCHNG (cu mm) | OIL FLOW GS XCHNG (g/hr) |
|---|---|---|---|---|---|---|
| 1500.00 | I | 1/2 crwn lnd (x2) | 0.04 | 1.51 | 0.00 | 0.00 |
| | II | top ring | 0.01 | 0.38 | -0.08 | -3.03 |
| | III | 1 ring width below | 1.11 | 42.01 | -0.23 | -8.70 |
| | IV | 2nd land | 2.30 | 87.04 | -0.52 | -19.68 |
| | V | 2nd ring | -0.02 | -0.64 | -0.11 | -4.16 |

| SAE-30 | | PISTON REGIONS | AVG VOL PWR STRK (cu mm) | OIL FLOW PWR STRK (g/hr) | AVG VOL GS XCHNG (cu mm) | OIL FLOW GS XCHNG (g/hr) |
|---|---|---|---|---|---|---|
| 3000.00 | I | 1/2 crwn lnd (x2) | -0.34 | -12.87 | -0.12 | -4.54 |
| | II | top ring | 0.08 | 3.03 | -0.21 | -7.95 |
| | III | 1 ring width below | 0.74 | 28.01 | -0.23 | -8.70 |
| | IV | 2nd land | 1.43 | 54.12 | -0.45 | -17.03 |
| | V | 2nd ring | 0.32 | 12.11 | -0.19 | -7.19 |

| 15W-40 | | PISTON REGIONS | AVG VOL PWR STRK (cu mm) | OIL FLOW PWR STRK (g/hr) | AVG VOL GS XCHNG (cu mm) | OIL FLOW GS XCHNG (g/hr) |
|---|---|---|---|---|---|---|
| 1500.00 | I | 1/2 crwn lnd (x2) | -0.04 | -1.51 | 0.08 | 3.03 |
| | II | top ring | 0.03 | 1.14 | -0.04 | -1.51 |
| | III | 1 ring width below | 0.63 | 23.84 | 0.05 | 1.89 |
| | IV | 2nd land | 1.17 | 44.28 | -0.08 | -3.03 |
| | V | 2nd ring | 0.16 | 6.06 | -0.01 | -0.38 |

| 15W-40 | | PISTON REGIONS | AVG VOL PWR STRK (cu mm) | OIL FLOW PWR STRK (g/hr) | AVG VOL GS XCHNG (cu mm) | OIL FLOW GS XCHNG (g/hr) |
|---|---|---|---|---|---|---|
| 3000.00 | I | 1/2 crwn lnd (x2) | -0.22 | -8.33 | -0.16 | -6.06 |
| | II | top ring | 0.10 | 3.78 | -0.20 | -7.57 |
| | III | 1 ring width below | 0.46 | 17.41 | -0.38 | -14.38 |
| | IV | 2nd land | 0.91 | 34.44 | -0.66 | -24.98 |
| | V | 2nd ring | 0.09 | 3.41 | -0.35 | -13.25 |

OIL FLOWS UP THE LINER:

| SAE-30 | PISTON REGIONS | | AVG VOL ALL STRK (cu mm) | OIL FLOW ALL STRK (g/hr) |
|---|---|---|---|---|
| 1500.00 | I | 1/2 crwn lnd (x2) | 0.04 | 1.51 |
| | II | top ring | -0.07 | -2.65 |
| | III | 1 ring width below | 0.88 | 33.30 |
| | IV | 2nd land | 1.78 | 67.36 |
| | V | 2nd ring | -0.13 | -4.81 |

| SAE-30 | | PISTON REGIONS | AVG VOL ALL STRK (cu mm) | OIL FLOW ALL STRK (g/hr) |
|---|---|---|---|---|
| 3000.00 | I | 1/2 crwn lnd (x2) | -0.46 | -17.41 |
| | II | top ring | -0.13 | -4.92 |
| | III | 1 ring width below | 0.51 | 19.30 |
| | IV | 2nd land | 0.98 | 37.09 |
| | V | 2nd ring | 0.13 | 4.92 |

| 15W-40 | | PISTON REGIONS | AVG VOL ALL STRK (cu mm) | OIL FLOW ALL STRK (g/hr) |
|---|---|---|---|---|
| 1500.00 | I | 1/2 crwn lnd (x2) | 0.04 | 1.51 |
| | II | top ring | -0.01 | -0.38 |
| | III | 1 ring width below | 0.68 | 25.73 |
| | IV | 2nd land | 1.09 | 41.25 |
| | V | 2nd ring | 0.15 | 5.68 |

| 15W-40 | | PISTON REGIONS | AVG VOL ALL STRK (cu mm) | OIL FLOW ALL STRK (g/hr) |
|---|---|---|---|---|
| 3000.00 | I | 1/2 crwn lnd (x2) | -0.38 | -14.38 |
| | II | top ring | -0.10 | -3.78 |
| | III | 1 ring width below | 0.08 | 3.03 |
| | IV | 2nd land | 0.25 | 9.46 |
| | V | 2nd ring | -0.26 | -9.84 |

# APPENDIX F DETERMINATION OF VOLUME DIFFERENCES

## F.1 DETERMINATION OF REGIONS

The program utilized uses a Crank-Nicolson technique to integrate the difference in areas under a film trace for the upstroke and downstroke pairs of specific regions. Subsequently, these area differences are swept around the circumference of the bore to determine the volume differences.

Each inputted region is calculated based on using the "zero-point" crank angle as a reference position. This position, initially determined to equal $-81.6^0$, is defined as the angle at which the top of the piston passes the quartz window on an upstroke. The following relation is then used to determine the distance, s, in cm, from the crank axis to the piston pin axis at this point:

$$s = a \times \cos(\theta) + (l^2 - (a^2 \times \sin^2(\theta))^{1/2}$$

where: l = connecting rod length = 11.01 cm
a = crank radius = 3.5 cm
$\theta$ = crank angle

Next, a new "zero-point" crank angle is obtained by fitting a model of the piston to a printout of the film trace. Since piston geometry is known, this step allows for an estimate in the error of the original "zero-point". This error distance is subtracted (or added) to the original s and a new "zero-point"crank angle is determined by iterating. Specific regions can then be determined in a similar manner.

For example:

a) the initial "zero-point" is $-81.6^o$. Therefore, $s_0 = 10.96$ cm

b) it is determined from the trace that the s is 0.05 cm off. Therefore, the new $s_0 = 10.96 - 0.05 = 10.91$ cm

c) by iterating, the new "zero-point" is determined to equal $-82.5^o$

d) the crown land is 0.95 cm long

e) therefore, the new $s = s_1 = s_o + d = 10.94 + 0.95 = 11.89$ cm

d) now iterate:
$\theta = -67.7^0$ implies $s_1 = 11.85$
$\theta = -67.9^0$ implies $s_1 = 11.84$
$\theta = -67.5^0$ implies $s_1 = 11.86$ (correct one)

e) the region relating to the crown land would then be $-82.5^0$ to $-67.5^0$

f) the top ring region is determined in a similar manner except now $s_0 = 11.91$ cm

Regions II, IV, and V consist of the top ring, second land, and second ring, respectively. They are used to reflect the film behavior of the upper portions of the piston. The crown land is not included based on the reasoning presented in section 6.2. Region I is determined based on the film on the liner as three centimeters of the crown land pass the window. The assumption is that the thickness on the liner at this point is the same up to TRR (top ring reversal). Finally, region III, one ring width below the top ring, is used in an attempt to substantiate the claim that oil is drawn up and around the top ring during operation.

## F.2 "MASSBAL.FOR" LISTING

```
C
      PROGRAM MASSBAL
C
C *** Program to compute up / down stroke oil volume differences in
C     distinct specified regions along the piston for multiple Sloan
C     data files and write them to an output file that can be
C     converted to a bar graph format.
C
C     This program requires as input any number of standard Sloan data
C     files containing an array of position vs film thickness. The program
C     will average the volume of oil in any number of user specified
C     regions along the piston.
c
c       The program has been adapted to analyze either McElwee
c       [where IRDATE(3)=89] or Bliven flor.* data sets.  Commands
c       specific to Lux [where IRDATE(3)=88] data sets have been
c       neutralized by comment lines which are specified by "cc".
c       [M. Bliven, 14 March 1990]
c
C
C *** Program structure:
C
C       Main Level    1st Sublevel    2nd Sublevel    3rd Sublevel
C       ________________________________________________________________
C       MASSBAL       FSTDCTPT
C                     INTEGRATEDF
C                     AVERAGE
C
C *** I/O
C
C        Unit     3:        INFILE Sloan data file
C        Unit     5:        Terminal I
C        Unit     6:        Terminal O
C        UNIT    10:        OUTFILE, BDC LOCATIONS, RPM
C
C *** important variables
C
C        AVALS              Array of average volume for like revolutions
C        CALOC              Crank angle location
C        NPMAX              parameter, max number of points to plot
C        CALFCTR            calibration factor for individual data set
C        CAOFFST            correction factor for shaft encoder offset
C        FILM(2,NPMAX)      Array of position vs film thickness
C        GEMNVAL            Mean value of oil volume difference for gas
C                           exchange strokes
C        GESD               Standard deviation for oil volume difference
C                           for gas exchange strokes
C        INFILEV            Input file vector
C        INTRPM             Value for engine speed calculated from time
C                           difference between BDC pulses
C        LWRB(10)           Lower bound for region i
C        MNVAL              Mean value of oil volume for a region for like
C                           revolutions from the program AVERAGE
C        NBDCLOC            Botton dead center location in crank angle
C        NSTROKE            Number of strokes recorded in data file
C        NUMFIL             Number of Sloan files to process
C        NUMREG             Number of regions to divide data into
C        OFFST              Instrument offset factor to initialize zero
C                            film thickness
C        PWMNVAL            Mean value of oil volume difference between
C                           powered strokes
C        PWSD               Standard deviation or oil volume difference
C                           between powered strokes
```

```
C       REGVAL          Array containing piston regions with the
C                       average value of oil volume difference for
C                       like revolutions
C       SIGVAL          Standard deviation of oil volume for like
C                       revolution from the program AVERAGE
C
C
        PARAMETER NPMAX = 190000          ! max  # of points/ch
        PARAMETER NPCMAX = 60000          ! max # of points/cycle
        PARAMETER NCMAX = 250             ! max# of cycles
        PARAMETER NREGMAX = 15
C
        INCLUDE 'SLNCOM.FOR'              ! contains IMPLICIT INTEGER*4
C
        INTEGER*2 IHED1(256),IHED2(256)
        EQUIVALENCE (IHED1,NRUN),(IHED2,NSLOT)
C
        INTEGER*2 IDATA(NPMAX)
C
        INTEGER NBDCLOC(NCMAX),NCHOICE, NSTROKE(NCMAX),
     $  NUMREV,PCH,ICH,Q,ICH1,CALOC(365),NUMREG
        REAL FILM(2,NPCMAX), AVALS(2,NCMAX), VALUE(2),
     $  XOLD,XNEW, INTRPM(NCMAX), CALFCTR,ROLOFF,CAPPT,
     $  XSCL(4),INTAR(10000),OUTAR(10000),DUMCT,
     $  SUM, VAL, OFFST,MNVAL, MNPOS, SIGVAL, SIGPOS,DUMPLOT,
     $  LSTROKE, CKRAD, CROL, BORE, CAOFFST, LWRB(NREGMAX),
     $  UPRB(NREGMAX), PWMNVAL(NREGMAX), PWSD(NREGMAX),
     $  GEMNVAL(NREGMAX), GESD(NREGMAX), REGVAL(NREGMAX,NCMAX)
C
        CHARACTER INFILEV(20)*40,OUTFILE*40,A*1,B*1,C*1,
     $  CALINT*3,STROKE*4,skip*3
C
C *** initialize:
C
        CALINT = 'ON'
        ICH = 3
C
C *** set up menu:
C
10      CONTINUE
        ISTAT = LIB$ERASE_PAGE(1,1)                ! erase page...
        WRITE (5,1000) CALINT
        READ (5,*,ERR = 10,END = 999) NCHOICE
C
C *** NCHOICE = 1: Set data files to read
C
        IF (NCHOICE.EQ.1) THEN
         WRITE (6,'('' How many flor.* files? (up to 20): '',$)')
         READ(5,*) NUMFIL
         DO I=1,NUMFIL
          WRITE (6,'('' Enter filename # '',I2,'': ''$)')I
          READ(5,'(A40)') INFILEV(I)
         ENDDO
        ENDIF
C
C *** NCHOICE = 2: Set piston regions by crank angle
C
        IF (NCHOICE.EQ.2) THEN
         WRITE (6,'('' How many piston regions? (up to 16): '',$)')
         READ(5,*) NUMREG
         DO I=1,NUMREG
          WRITE (6,'('' Enter lower, then upper bound (CA deg) for
     $  region # '',I2,'': ''$)')I
```

```
          READ(5,*) LWRB(I), UPRB(I)
         ENDDO
        ENDIF
C
C *** NCHOICE = 3: Linearly interpolate between crank angles
C
        IF (NCHOICE.EQ.3) THEN
          WRITE(6,'(1X''Linearly interpolate between crank angles?
     $  (y/n)'',$)')
          READ(5,'(A1)') C
          IF (C.EQ.'Y'.OR.C.EQ.'y') CALINT='ON'
          IF (C.EQ.'N'.OR.C.EQ.'n') CALINT='OFF'
        ENDIF

C
C *** NCHOICE = 4: Check entered information ***
C
C       Note: The running time of the program could be lengthy
C       depending on the number of data files and regions specified.  It is
C       wise to check the input data for accuracy prior to execution.
C
        IF (NCHOICE.EQ.4) THEN
          ISTAT = LIB$ERASE_PAGE(1,1)    !erase page
          DO I = 1, NUMFIL
            WRITE (6,'('' Data File # '',I3,'' is: '',A40)')I,
     $      INFILEV(I)
          ENDDO
          DO I = 1, NUMREG
            WRITE (6,'('' Crank angles bounding region #'',I2,
     $      '' are: '',F7.2,'' to'',F7.2)')I, LWRB(I), UPRB(I)
          ENDDO
          WRITE (6,'('' RTN to continue '',$)')
          READ(5,'(A1)') B
        ENDIF
C
C *** NCHOICE = 5 Execute main program and write output.
C
        IF (NCHOICE.EQ.5) THEN
          DO I = 1, NUMFIL
            ISTAT = LIB$ERASE_PAGE(1,1)    !erase page
            WRITE (5,1001) CALINT, INFILEV(I)
            ILUN = 3
            OPEN(UNIT=ILUN,NAME=INFILEV(I),TYPE='OLD',ACCESS='DIRECT'
     $ ,FORM='UNFORMATTED')
C
C *** and read header:
C
        READ (ILUN'1) (IHED1(L),L=1,256)
        READ (ILUN'2) (IHED2(L),L=1,256)
C
        IDUM = 1
        MPPC = IDUM*NBPC*256
C
C *** load up the private common
C
C     These values are user specified prior to data collection.
C
        CAPPT = RUSER(26)        ! crank angles per point
        LSTROKE = RUSER(27)      ! engine stroke                 [cm]
        BORE   = RUSER(28)       ! engine bore                   [cm]
        CRDL   = RUSER(29)       ! connecting rod length         [cm]
C
C *** Convert to mm
```

```
C
        BORE = BORE* 10.
        LSTROKE = LSTROKE*10.
        CRDL = CRDL*10
        CKRAD = LSTROKE /2.
C
C *** Set shaft encoder error in variable CAOFFST
C
C       The shaft encoder marks the crank angle at BDC. Depending on
C       certain errors the recorded BDC position is not necessarily at -180.
C
c1      IF (IRDATE(3).EQ.88) THEN
cc        CAOFFST = -178.5
cc      ELSE
          if (irdate(3).eq.89.and.nrun.gt.99.and.nrun.lt.106) then
            caoffst = -181
          else
            if (irdate(3).eq.90) then
              caoffst = -180.926
            else
              CAOFFST = -180
            endif
          endif
cc      ENDIF
C
C *** Look for old BDC file. The BDC file contains the specific
C       calibration factor and the number of revolutions in the data set.
C
        OUTFILE = ' '
        ENCODE(40,'(''BDCLOC.'',I3)',OUTFILE)NRUN
C
C *** Open existing BDC file
C
        OPEN(UNIT=10,NAME=OUTFILE,TYPE='OLD',ACCESS='SEQUENTIAL',
     $       FORM='FORMATTED')
        READ(10,*) CALFCTR, NUMREV
        DO J=1,NCMAX
          READ(10,*,END=15,ERR=5) NBDCLOC(J),INTRPM(J),NSTROKE(J)
        ENDDO
 15     CONTINUE
C
C *** Set region along piston to analyze
C
          DO N = 1, 2
            DO J=1,NUMREG
              DO L=1,NUMREV
                REGVAL(J,L) = 0.0
              ENDDO
            ENDDO
            M = 1
            DO K=N, NUMREV-1, 2
              IFPT=NBDCLOC(K)
C
C *** Set IFPT and NRPTS Set PCH for labels
C
              NRPTS = NBDCLOC(K+1) - NBDCLOC(K) + 1 ! # of points to read
              IF (NRPTS.GT.NPMAX) NRPTS = NPMAX
C
C *** Linearly interpolate between crank angles
C
        IF (CALINT.EQ.'OFF') GOTO 21
        ICH1 = 1
C
```

```
      CALL FSTDGTPT(ILUN,ICH1,IFPT,NRPTS,IDATA)
C
      NUMCA = 0
      XOLD = CSCL(ICH1)*IDATA(1)+CBIA(ICH1)
c2    IF (NRUN.LT.47.and.irdate(3).eq.88) XOLD=XOLD-5.0
cc    IF (NRUN.GT.47.and.irdate(3).eq.88) XOLD=XOLD+5.0
      skip = 'no'
C
      DO L=2, NRPTS
        XNEW = CSCL(ICH1)*IDATA(L)+CBIA(ICH1)
c3      IF (NRUN.LT.47.and.irdate(3).eq.88) XNEW=XNEW-5.0
cc      IF (NRUN.GT.47.and.irdate(3).eq.88) XNEW=XNEW+5.0
        IF (XNEW.GT.2.5.AND.XOLD.LT.2.5) THEN
         if (cappt.eq..5.and.skip.eq.'yes') then
          skip = 'no'
          go to 20
         endif
         if (cappt.eq..5.and.skip.eq.'no ') skip='yes'
          NUMCA=NUMCA+1
          CALOC(NUMCA)=L + IFPT
20      ENDIF
        XOLD=XNEW
      ENDDO              ! END OF L LOOP FOR CRANK ANGLE LOCATION
21    CONTINUE
C
C *** Average first 100 data points of pmt signal to
C     establish zero offset.  .005 sets this to 2 microns
C
c1    NOTE:  This section adapted to analyze data collected
cc    by BLIVEN whose PMT signal due to instrument offset and
cc    laser reflectances alone (ie. dry liner) was measured to be
cc    approximately 0.008 V.  Averaging over first 100 data points
cc    is by-passed and offset value is set to 0.008.
cc
        CALL FSTDGTPT(ILUN,ICH,IFPT,NRPTS,IDATA)
c
        if (irdate(3).eq.89) then
          SUM =0.
          DO L =300, 400
            VAL = CSCL(ICH)*IDATA(L) + CBIA(ICH)
            SUM = SUM + VAL
            DUMCT = L-299
          ENDDO ! END OF L LOOP FOR OFFSET
c
          OFFST = SUM/DUMCT-.016  ! zero pt offset for McElwee
        else
          OFFST = .0              ! zero pt offset for Bliven
        endif
C
C *** Convert the data and write them into plot-array
C
C       Note: CLKRTE is clock-rate in [kHz] and can be used to
C       convert x-axis data time
C
        DUMPLOT= CAOFFST
        Q=1
        DO L = 1,NRPTS
C
C *** Convert time to crank angle by speed or position interpolation
C
        IF (CALINT.EQ.'OFF') THEN
          FILM(1,L) = CAOFFST + 360.*FLOAT(L-1)/FLOAT(NRPTS-1)
        ELSE
```

```
C
C *** If Crank angle pulse is coincident with sample number, then
C     increment x value by one crank angle
C
            IF ((L+IFPT).EQ.CALOC(Q)) THEN
              FILM(1,L) = CAOFFST + FLOAT(Q)
              DUMPLOT=FILM(1,L)
              Q=Q+1
            ELSE
C
C *** Otherwise divide fractions of crank angle evenly between pulses
C
              IF (Q.EQ.1) THEN
               FILM(1,L) = CAOFFST+FLOAT(L-1)/FLOAT(CALOC(Q)-IFPT)
              ELSE
               FILM(1,L)=DUMPLOT+1.0/FLOAT((CALOC(Q)-CALOC(Q-1)))
               DUMPLOT=FILM(1,L)
              ENDIF
            ENDIF
           ENDIF
           FILM(2,L)=(CSCL(ICH)*IDATA(L)+CBIA(ICH)-OFFST)/CALFCTR
ccc
ccc        write(6,'(''FILM(2,L) = '',f10.5)') film(2,l)
ccc        write(6,'(2i3,i6,2f8.3)')n,k,l,film(1,l),film(2,l)
ccc
           ENDDO    ! END OF L LOOP FOR FILM ARRAY
C
C *** Call integration routine for each region. Program INTEGRATEDF
C     will calculate the volume of oil in a specified region for one
C     revolution.
C
        DO J=1, NUMREG
          CALL INTEGRATEDF(FILM,LWRB(J),UPRB(J),VALUE,NRPTS,CRDL,
     $        CKRAD)
          REGVAL(J,M) = VALUE(2)*BORE*3.14159
ccc
ccc     write(6,'(4i3,3e10.4)')m,n,k,j,value(1),value(2),regval(j,m)
ccc
        ENDDO  ! END J LOOP FOR REGIONS
          AVALS(1,M) = VALUE(1)
          M=M+1
        ENDDO  ! END OF K LOOP FOR ALL REVOLUTIONS OF 1 TYPE
C
C *** Call average routine for like revolutions of one region. Program
C     AVERAGE will calculate the average volume for the like revolutions.
C
       DO J=1,NUMREG
           DO L = 1, NUMREV
             AVALS(2,L) = 0.
           ENDDO
         DO L=1,M
           AVALS(2,L) = REGVAL(J,L)
         ENDDO
         CALL AVERAGE(AVALS,MNVAL,MNPOS,SIGVAL,SIGPOS)
         IF (NSTROKE(N).EQ.1) THEN
           PWMNVAL(J) = MNVAL
           PWSD(J) = SIGVAL
         ELSE
           GEMNVAL(J) = MNVAL
           GESD(J) = SIGVAL
         ENDIF
       ENDDO  ! END OF J LOOP (DIFFERENT REGIONS)
       ENDDO  ! END OF N LOOP (DIFFERENT REVOLUTION TYPES)
```

```
C
C *** Write output to a file with format massbal.# file
C
        ENCODE (40,'(''[BLIVEN.DATA.MASS]MASSBAL.'',I3)',OUTFILE) NRUN
        OPEN (UNIT=10,FILE=OUTFILE,TYPE='NEW',ACCESS='SEQUENTIAL',
     $  FORM='FORMATTED')
c
        write (10,'(1x'' '')')
        write (10,'(28x''|________________|  '')')
        write (10,'(28x''| MASSBAL RESULTS |  '')')
        write (10,'(28x''|________________|  '')')
        write (10,'(1x'' '')')
        write (10,'(28x''Data Set: '',a15)')infilev(i)
        write (10,'(1x'' '')')
        write (10,'(1x'' '')')
c
        WRITE(10,'(5X''                                  POWER STROKES        GAS
     $ EXCHANGE'')')
        write(10,'(5x''                                  ________________    _____
     $____________'')')
        WRITE(10,'(5X''REG     FRM       TO         MEAN       STD DEV      MEAN
     $  STD DEV'')')
        WRITE(10,'(5X'' #    (deg)     (deg)      (cu mm)     (cu mm)     (cu mm)
     $  (cu mm)'')')
        write(10,'(5x''___  _______   _______    ________    ________    _______
     $ _________'')')
        DO L =1, NUMREG
          write (10,'(1x'' '')')
          WRITE (10,'(5X,I2,1X,F7.2,2X,F7.2,4(3X,F7.2))')L, LWRB(L),
     $    UPRB(L), PWMNVAL(L), PWSD(L), GEMNVAL(L), GESD(L)
        ENDDO
        write (10,'(1x'' '')')
        write (10,'(1x'' '')')
        write (10,'(1x'' '')')
        write (10,'(1x'' '')')
        write (10,'(1x''NOTE: If negative crank angle regions specified,
     $ then POSITIVE mean values indicate '')')
        write (10,'(1x''      that UPstroke volumes are GREATER than
     $ DOWNstroke volumes.'')')
        write (10,'(1x''      Standard deviations are always positive.'')')
        ENDDO   ! END OF I LOOP (MULTIPLE FILE)
        ENDIF   ! END OF NCHOICE 5 IF LOOP
C
C *** Final Branch
C
 5      CONTINUE
        IF (NCHOICE.NE.0) GOTO 10
C
999     CONTINUE
C
C
C *** Formats:
C
1000    FORMAT (/' *** OIL FILM STATISTICAL ANALYSIS ***',///,
     $T10,'(1) Enter files to analyze. ',/,
     $T10,'(2) Set piston regions. ',/,
     $T10,'(3) Linear Crankangle Interpolation:',1x,A3,/,
     $T10,'(4) Check information for 1 & 2. ',/,
     $T10,'(5) Compute averages and write to massbal file.',/,
     $T10,'(0) or CTRL↑Z for exit'///,
     $' Enter choice: ',$)
1001    FORMAT (/' *** OIL FILM STATISTICAL ANALYSIS ***',///,
     $T10,'(1) Enter files to analyze. ',/,
```

```
     $T10,'(2) Set piston regions. ',/,
     $T10,'(3) Linear Crankangle Interpolation:',1x,A3,/,
     $T10,'(4) Check information for 1 & 2. ',/,
     $T10,'(5) Processing file: ',A30,' Be patient!',/,
     $T10,'(0) or CTRL↑Z for exit'///,
     $' Enter choice: ',$)
      STOP
C
      END
```

F.3 "INTEGRATEDF.FOR" LISTING

```
C
      SUBROUTINE INTEGRATEDF (FILM,LBD,UBD,VALUE,NRPTS,CRDL,CKRAD)
C
C *** This suboutine integrates the value in Film(2,i) using the Crank-
C     Nicholsen method.  It reads the step size from the first row of
C     Film.  The range is user-specified with lower and upper bounds.
C     The difference between areas of successive strokes is found and
C     returned to the driver program for averaging.
C
C *** DIMENSION AND DECLARE VARIABLES
C
      PARAMETER NPMAX = 250000          ! max  # of points/ch
      PARAMETER NPCMAX = 60000          ! max # of points/cycle
      PARAMETER NCMAX = 250             ! max# of cycles
C
      REAL FILM(2,NPCMAX),LBD,UBD, VALUE(2), AREA, POSA, POSB,
     $ CRDL, CKRAD, DMBD
      INTEGER I,J,K, NRPTS
C
C *** SET INITIAL CONDITIONS  BEFORE INTEGRATING
C
      J = 1
 6    K = 1
      DO I=1,NRPTS
        IF (LBD.GE.FILM(1,I)) THEN
          K=I
ccc
ccc       write(6,'(2f10.3)')lbd,film(1,k)
ccc
        ELSE
          GOTO 8
        ENDIF
      ENDDO
 8    CONTINUE
C
C *** Perform integration
C
      AREA = 0.
 10   IF (FILM(1,K+1).LE.UBD) THEN
        POSA = CKRAD*COS(FILM(1,K)/360.*2*3.141593)+
     $SQRT(CRDL**2 - (CKRAD**2)*(SIN(FILM(1,K)/360.*2*3.141593))**2)
        POSB = CKRAD*COS(FILM(1,K+1)/360.*2*3.14159)+
     $SQRT(CRDL**2 - (CKRAD**2)*(SIN(FILM(1,K+1)/360.*2*3.14159))**2)
C
C *** Divide by 1000. to convert microns to mm
C
        AREA=AREA+((FILM(2,K)+FILM(2,K+1))/1000.)*
     $     ABS((POSB-POSA)/2.)
        K = K+1
ccc
ccc     write(6,'(3e10.3)')posa,posb,area
ccc
        GOTO 10
      ENDIF
ccc
ccc     write(6,'(2f10.3,e10.3)')film(1,k),film(2,k),area
ccc
C
C *** Mirror bounds and find the area of the adjacent downstroke,
C     then subtract the values and return.
C
      IF (J.EQ.1) THEN
        DMBD = LBD
```

```
          LBD = -UBD
          UBD = -DMBD
          VALUE(1) = AREA
          J = 2
          GOTO 6
        ENDIF
        VALUE(1) = VALUE(1) - AREA
        VALUE(2) = VALUE(1)
C
C *** Return bounds to original values
C
        DMBD = LBD
        LBD = -UBD
        UBD = -DMBD
C
C *** That's the end
C
        RETURN
        END
```

## F.4 "AVERAGE.FOR" LISTING

```
C
      SUBROUTINE AVERAGE(AVALS,MNVAL,MNPOS,SIGVAL,SIGPOS)
C
C *** SUBROUTINE COMPUTES AVERAGE VALUES AND STANDARD DEVIATION
C     FOR THE FEATURE OF INTEREST N PASSED IN MATRIX 'AVALS'
C
C *** DIMENSION AND DECLARE VARIABLES
C
      PARAMETER NPMAX = 250000          ! max  # of points/ch
      PARAMETER NPCMAX = 60000          ! max # of points/cycle
      PARAMETER NCMAX = 250             ! max# of cycles
C
      REAL AVALS(2,NCMAX),MNVAL,MNPOS,SIGVAL,SIGPOS
     $ XSUM, SUMPOS, XVAL, DMCT, XDEV, POSDEV, SDSUM, SDPSUM
      INTEGER I,J,K
      I=1
      XSUM=0.
      SUMPOS=0.
 10   IF (AVALS(2,I).NE.0.0) THEN
        XVAL = AVALS(2,I)
        XSUM = XSUM + XVAL
        SUMPOS = SUMPOS + AVALS(1,I)
        DMCT = I
        I=I+1
        GOTO 10
      ENDIF
      MNVAL = XSUM/DMCT
      MNPOS = SUMPOS/DMCT
C
      I=1
      SDSUM=0.
      SDPSUM=0.
 12   IF(AVALS(2,I).NE.0.0) THEN
        XDEV = (AVALS(2,I) -MNVAL)**2
        POSDEV = (AVALS(1,I) - MNPOS)**2
        SDSUM = SDSUM + XDEV
        SDPSUM = SDPSUM + POSDEV
        DMCT = I
        I=I+1
        GOTO 12
      ENDIF
      SIGVAL=SQRT(SDSUM/DMCT)
      SIGPOS=SQRT(SDPSUM/DMCT)
      RETURN
C
      END
```

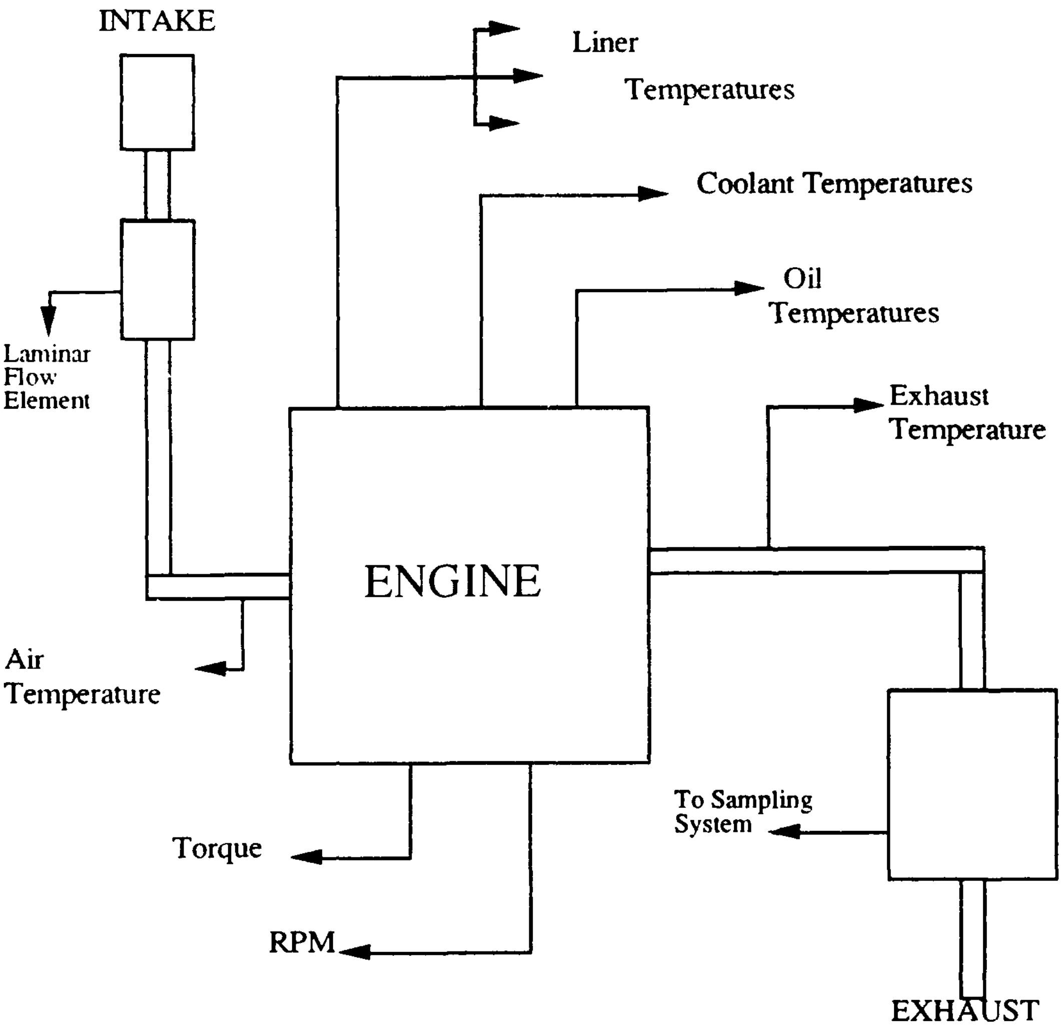



Figure 1. Engine Instrumentation/Measurement Equipment

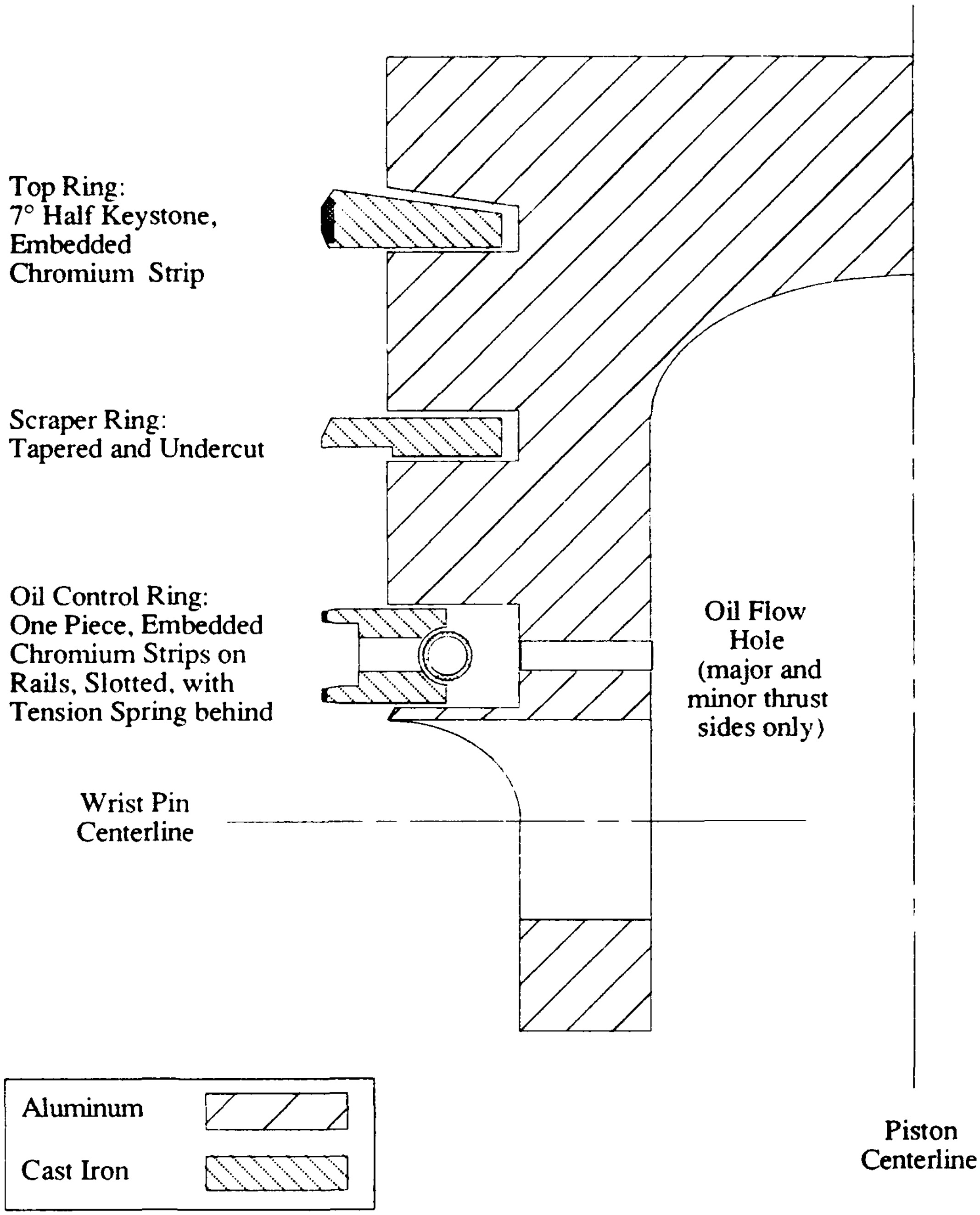



Figure 2. Piston and Rings of the Kubota EA300N

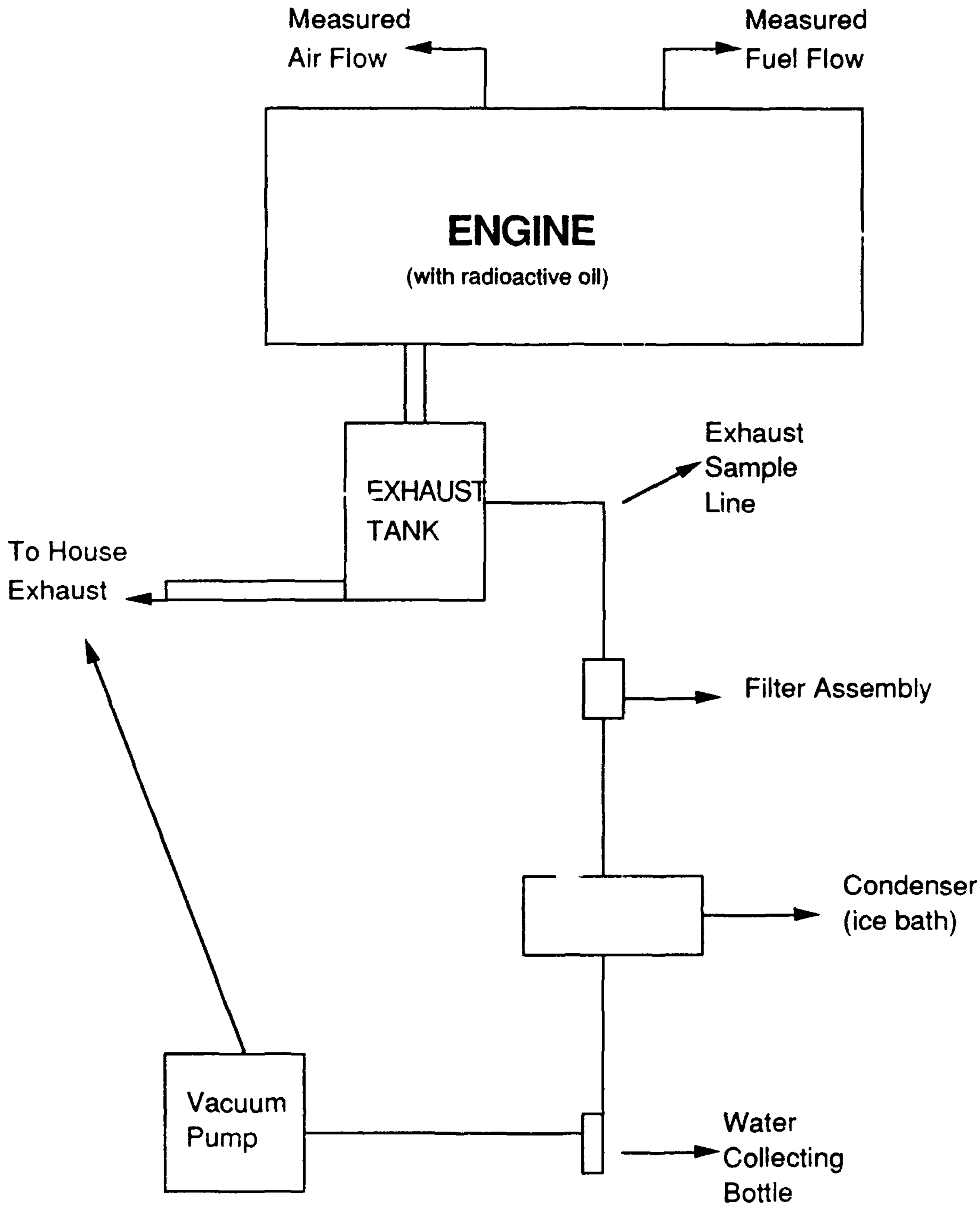



Figure 3. Schematic of Sampling System

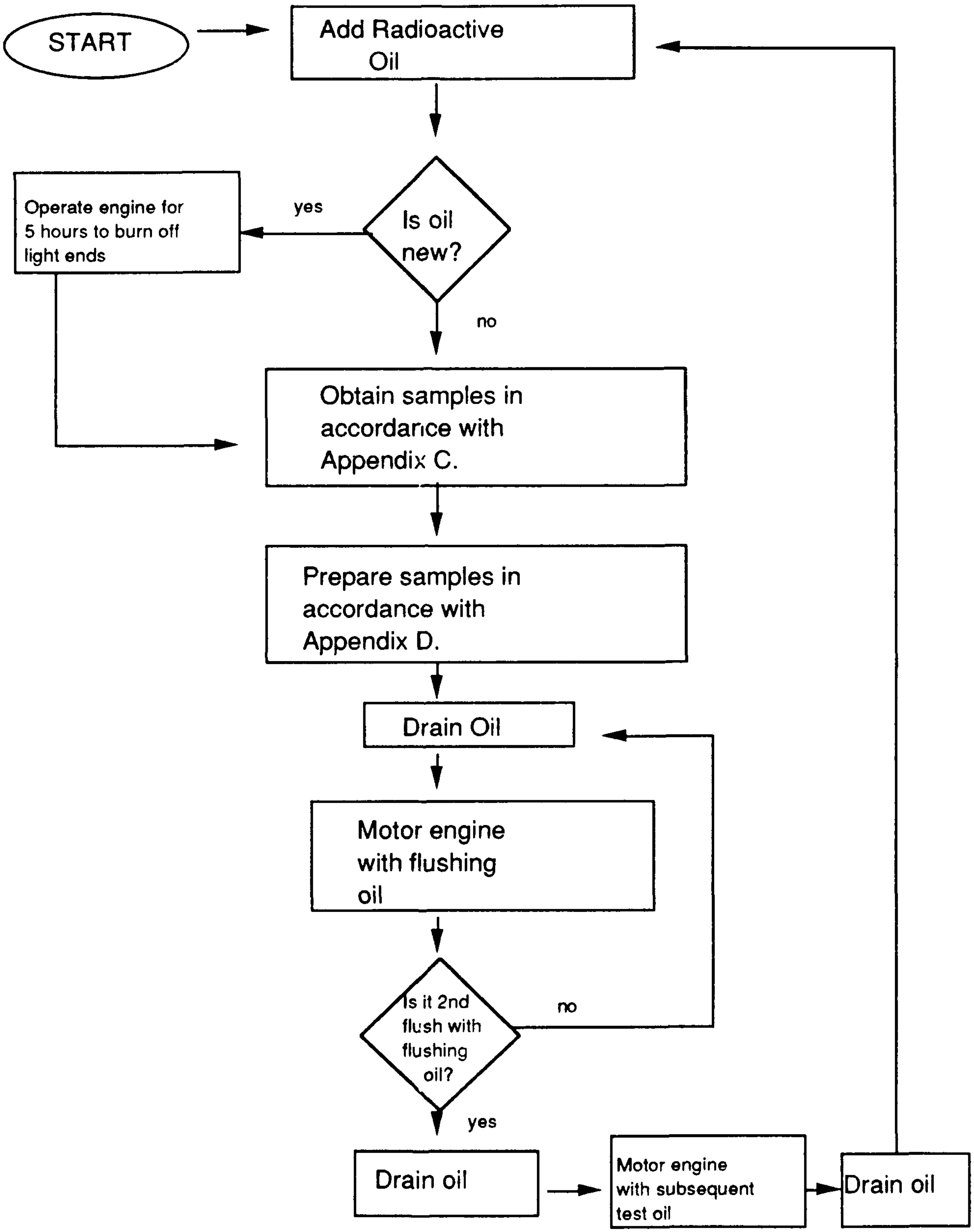



Figure 4. Procedural Flow Chart

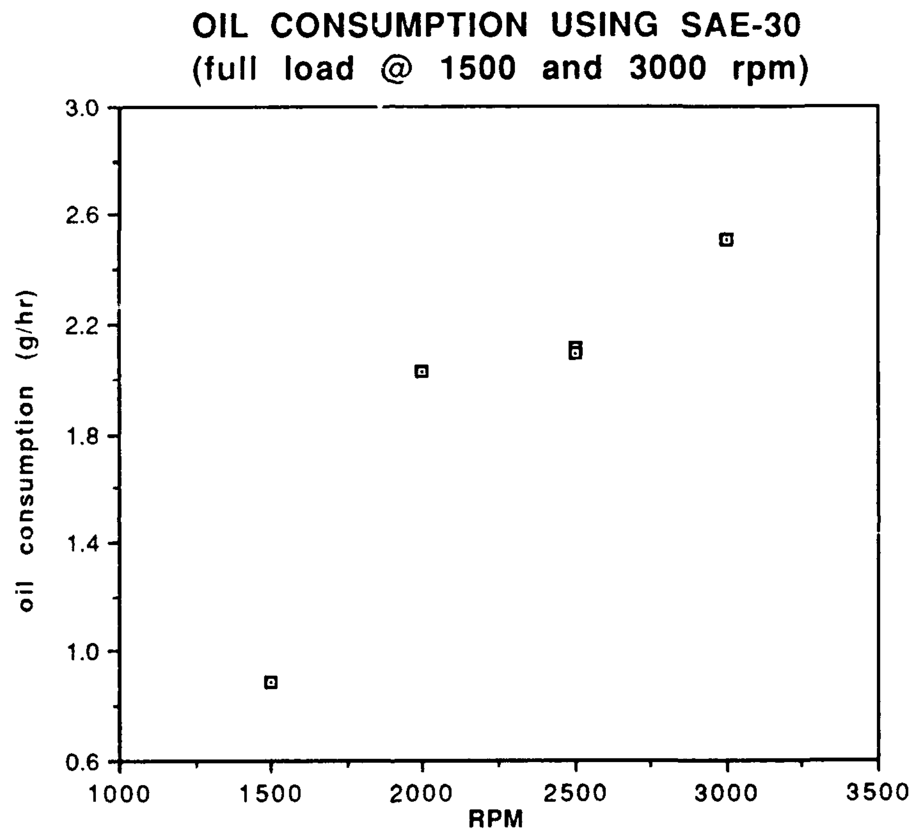

OIL CONSUMPTION USING SAE-30
(full load @ 1500 and 3000 rpm)
oil consumption (g/hr)
3.0
2.6
2.2
1.8
1.4
1.0
0.6
1000
1500
2000
2500
3000
3500
RPM

Figure 5

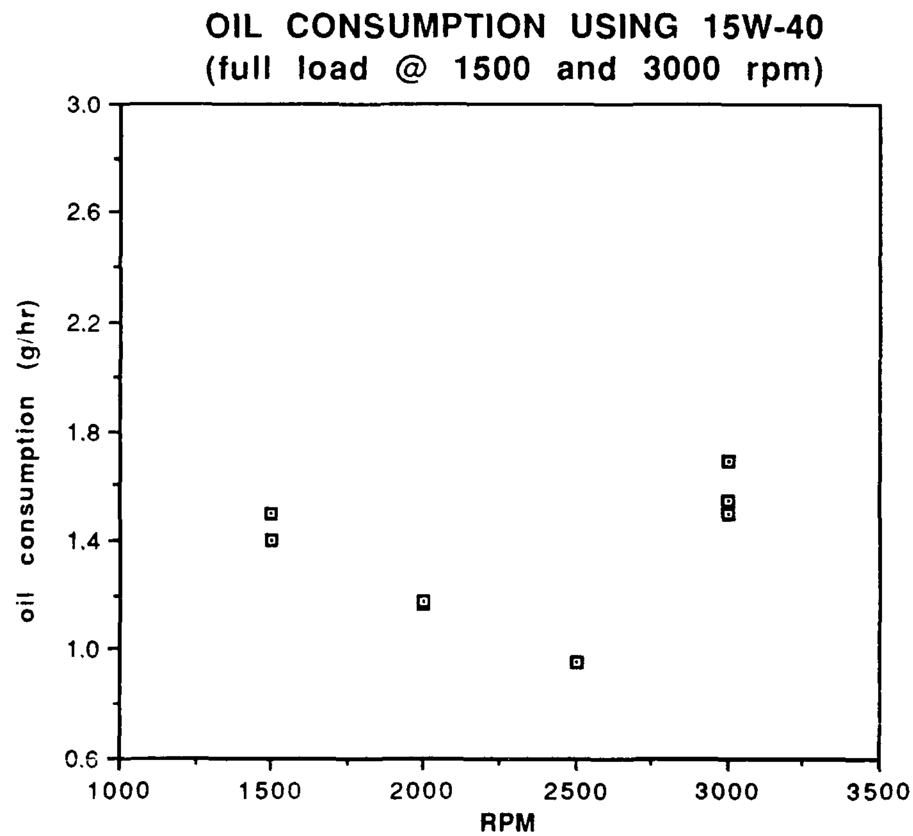

OIL CONSUMPTION USING 15W-40
(full load @ 1500 and 3000 rpm)
oil consumption (g/hr)
3.0
2.6
2.2
1.8
1.4
1.0
0.6
1000
1500
2000
2500
3000
3500
RPM

Figure 6

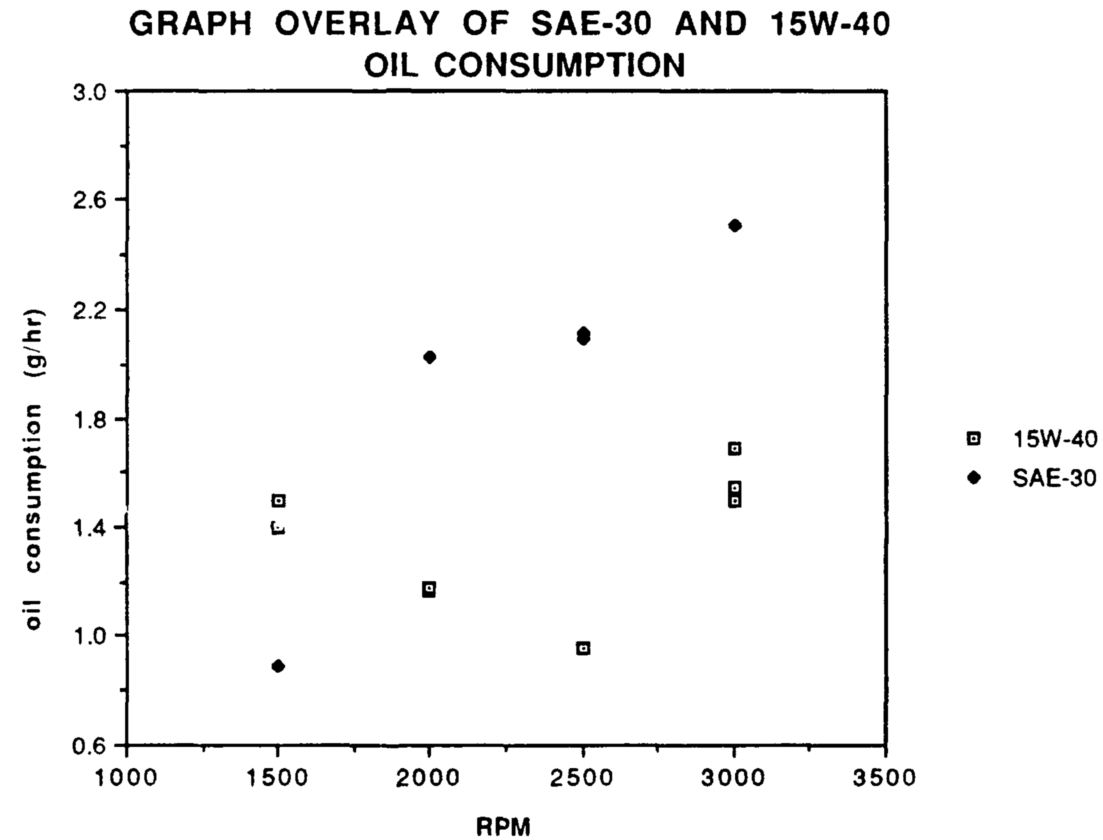

GRAPH OVERLAY OF SAE-30 AND 15W-40
OIL CONSUMPTION
oil consumption (g/hr)
3.0
2.6
2.2
1.8
1.4
1.0
0.6
1000
1500
2000
2500
3000
3500
RPM
15W-40
SAE-30

Figure 7

COMPARISON OF THE OIL CONSUMPTIONS USING SAE-30 AND 15W-40

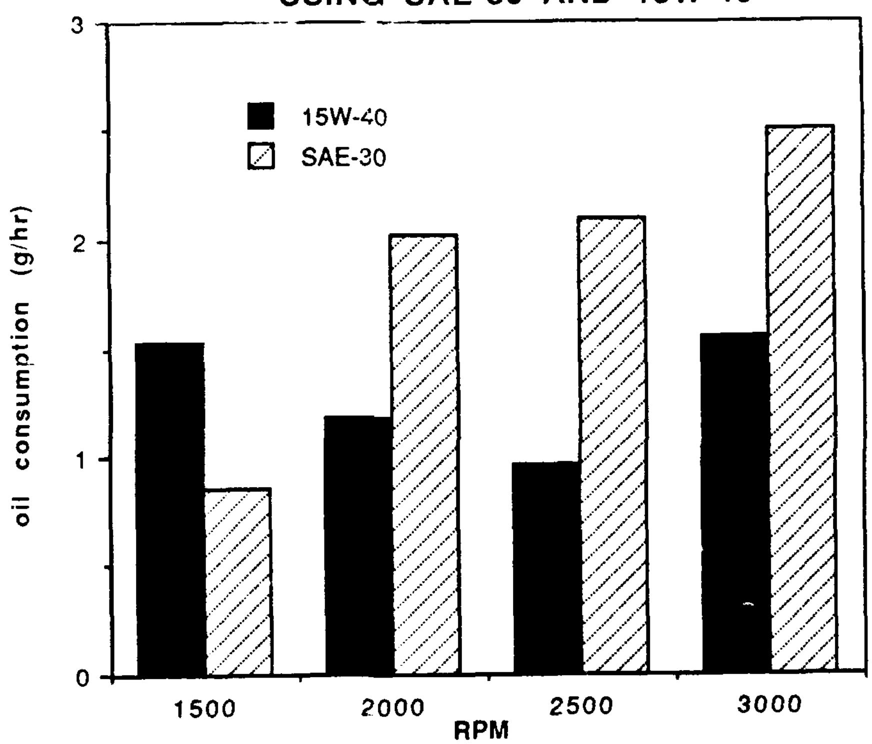



Figure 8

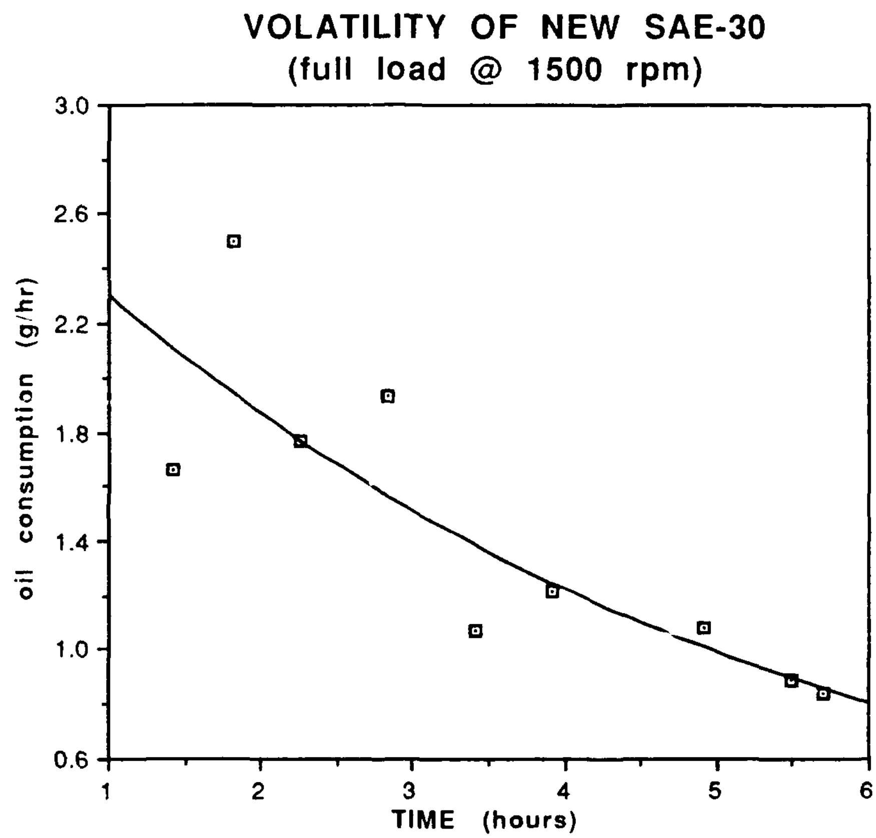

VOLATILITY OF NEW SAE-30
(full load @ 1500 rpm)
oil consumption (g/hr)
3.0
2.6
2.2
1.8
1.4
1.0
0.6
1
2
3
4
5
6
TIME (hours)

Figure 9

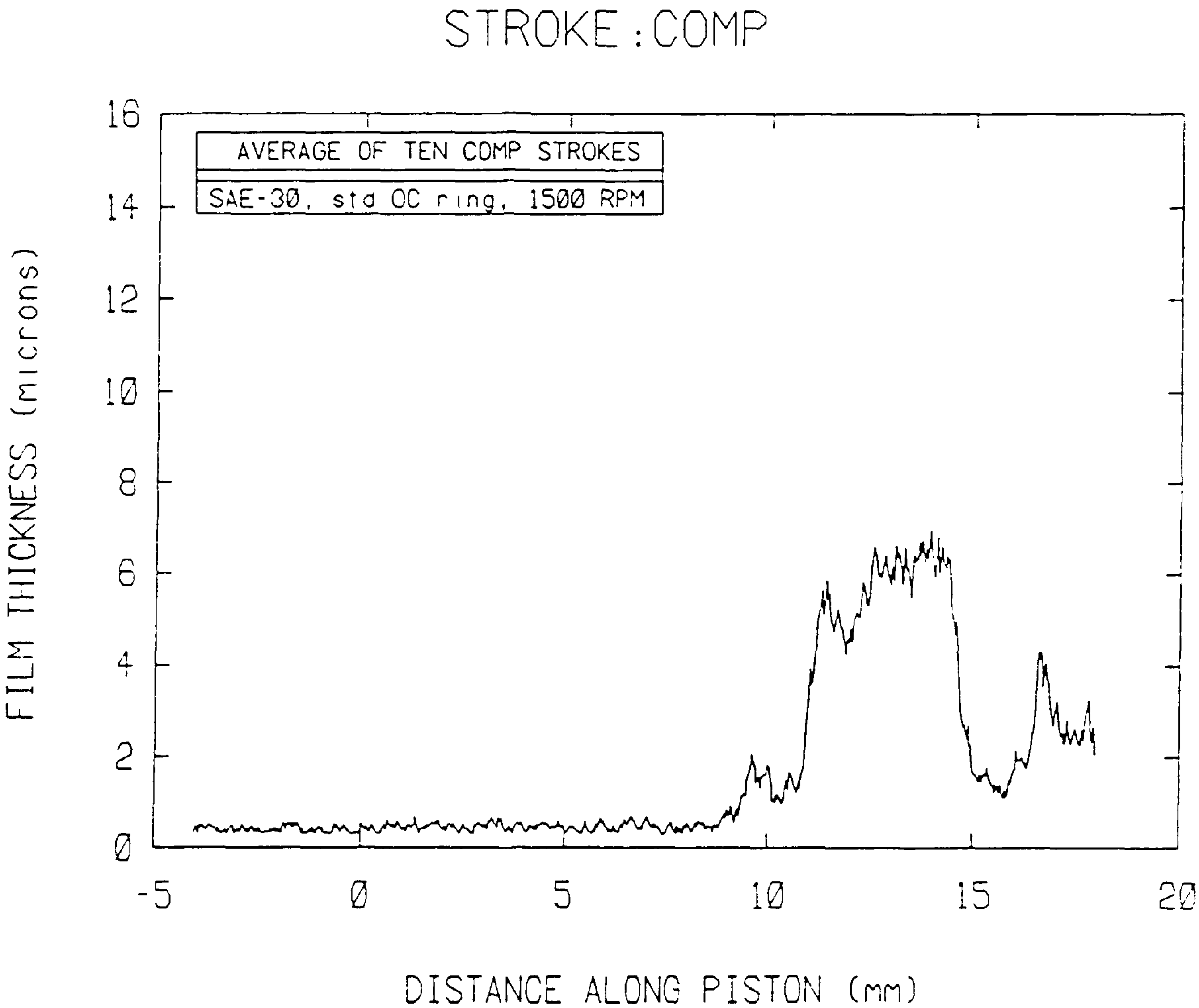

STROKE:COMP
AVERAGE OF TEN COMP STROKES
SAE-30, std OC ring, 1500 RPM
FILM THICKNESS (microns)
DISTANCE ALONG PISTON (mm)
16
14
12
10
8
6
4
2
0
-5
0
5
10
15
20

Figure 10

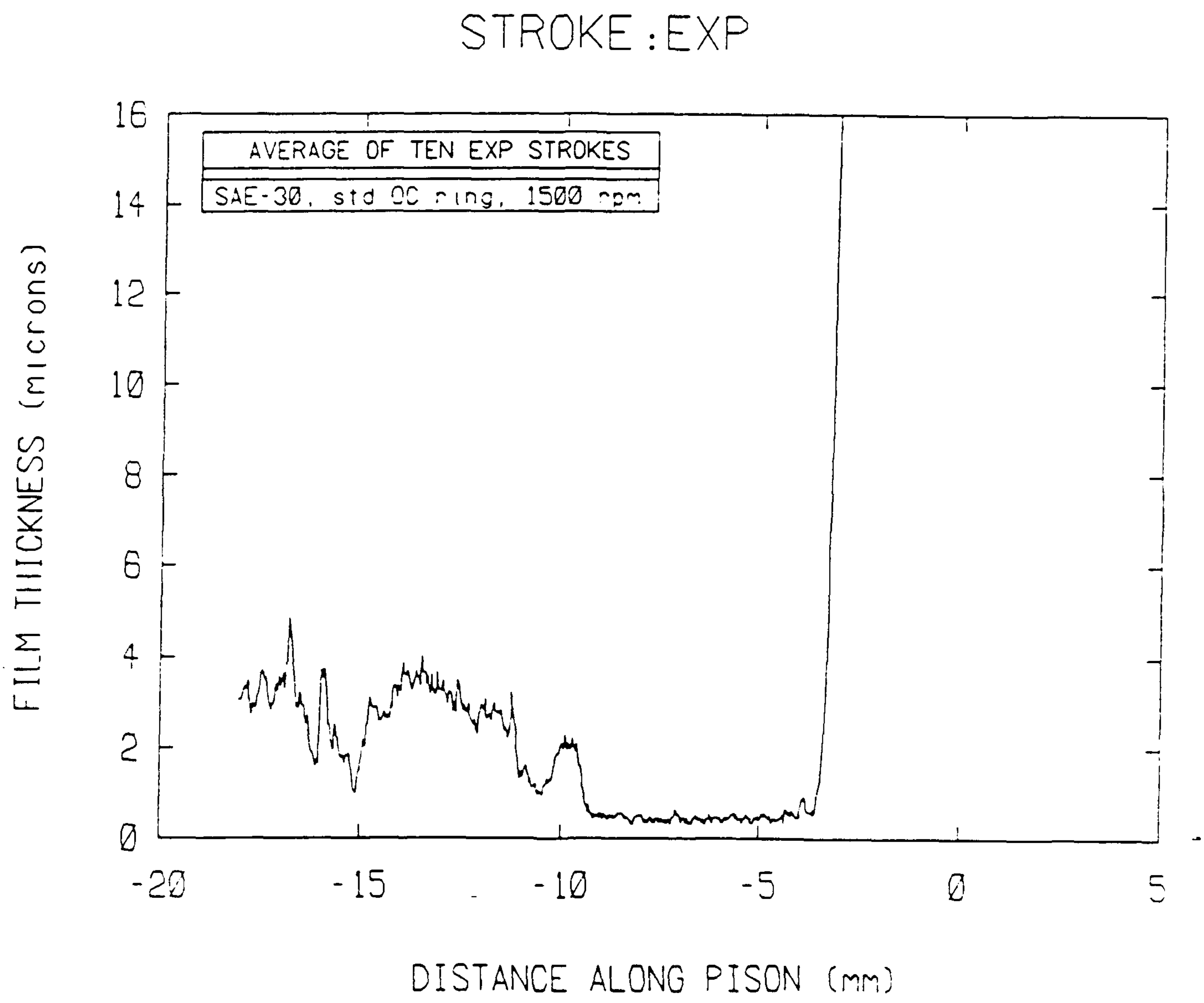

STROKE:EXP
AVERAGE OF TEN EXP STROKES
SAE-30, std OC ring, 1500 rpm
FILM THICKNESS (microns)
16
14
12
10
8
6
4
2
0
-20
-15
-10
-5
0
5
DISTANCE ALONG PISON (mm)

Figure 11

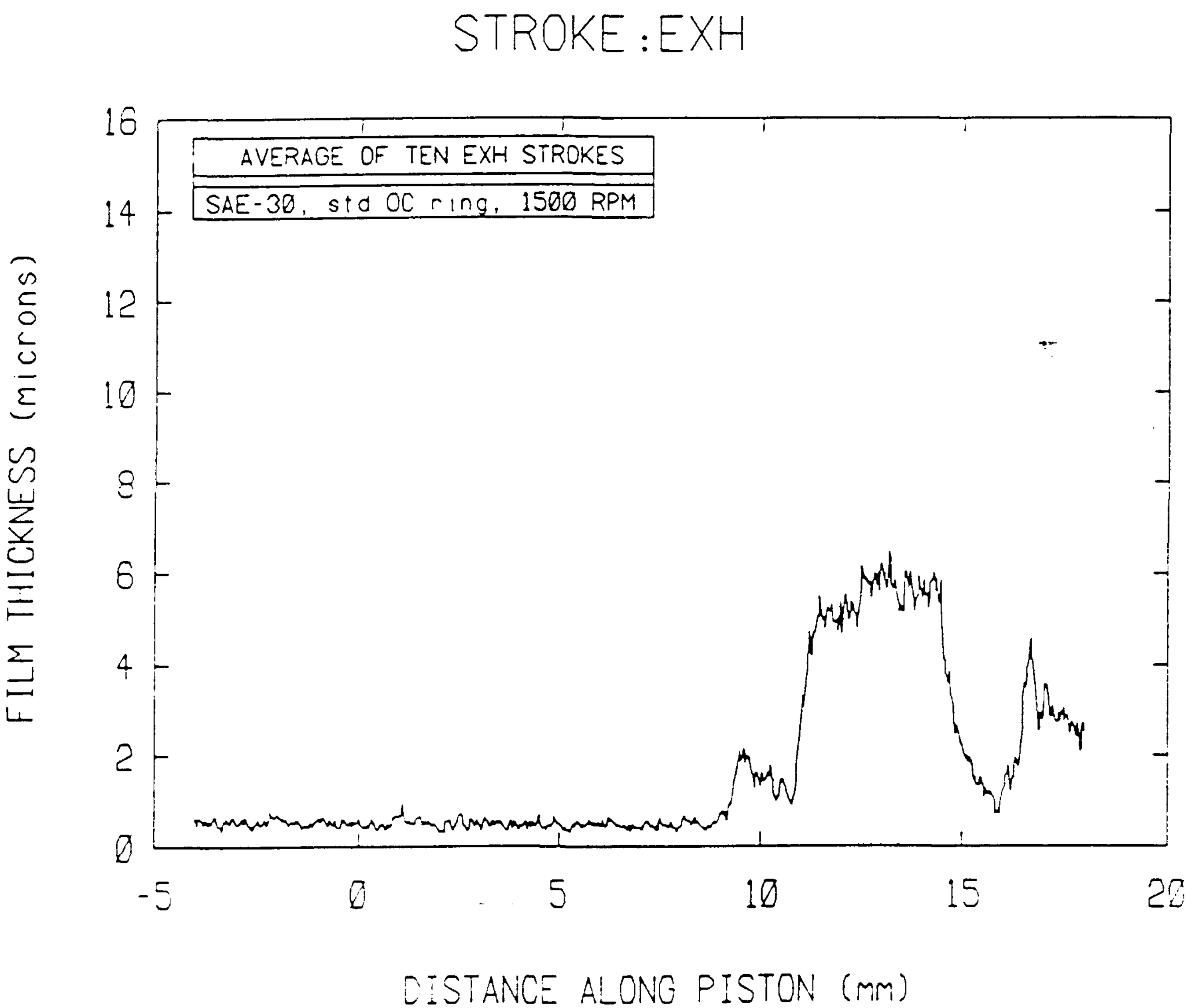

STROKE:EXH
AVERAGE OF TEN EXH STROKES
SAE-30, std OC ring, 1500 RPM
FILM THICKNESS (microns)
16
14
12
10
8
6
4
2
0
-5
0
5
10
15
20
DISTANCE ALONG PISTON (mm)

Figure 12

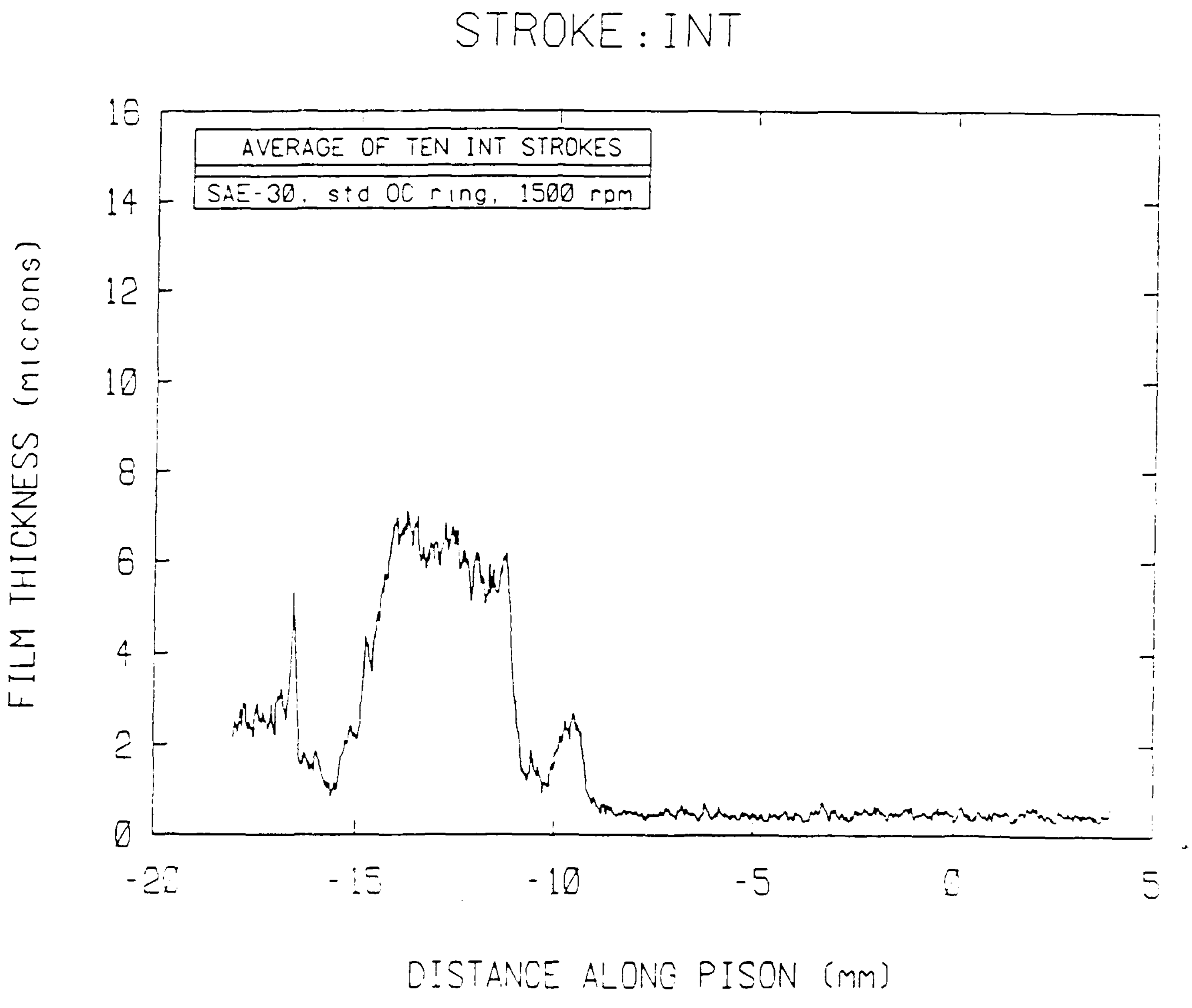

STROKE: INT
AVERAGE OF TEN INT STROKES
SAE-30, std OC ring, 1500 rpm
FILM THICKNESS (microns)
DISTANCE ALONG PISON (mm)
16
14
12
10
8
6
4
2
0
-20
-15
-10
-5
0
5

Figure 13

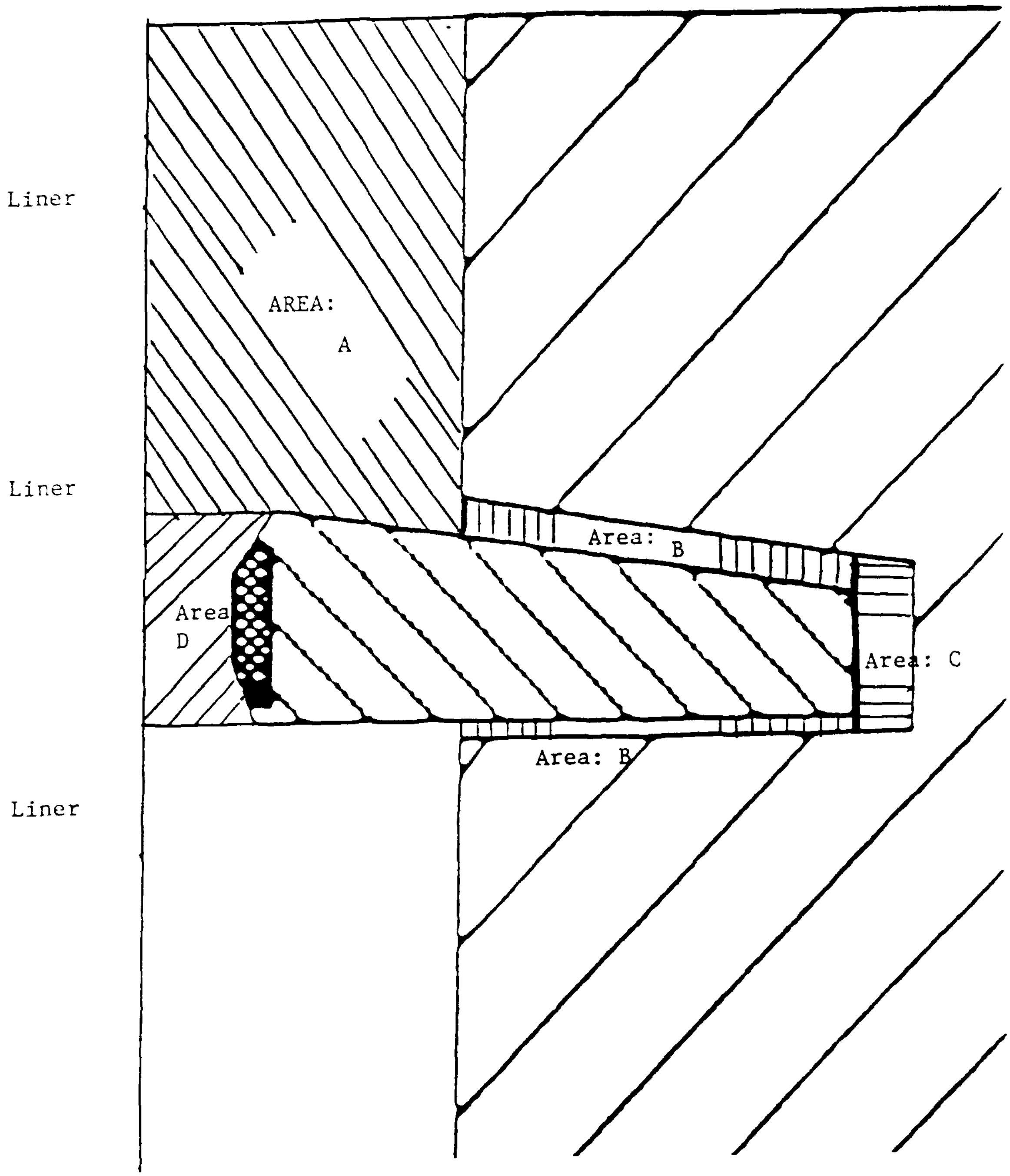



Figure 14. Areas/Volumes of possible oil consumption mechanisms

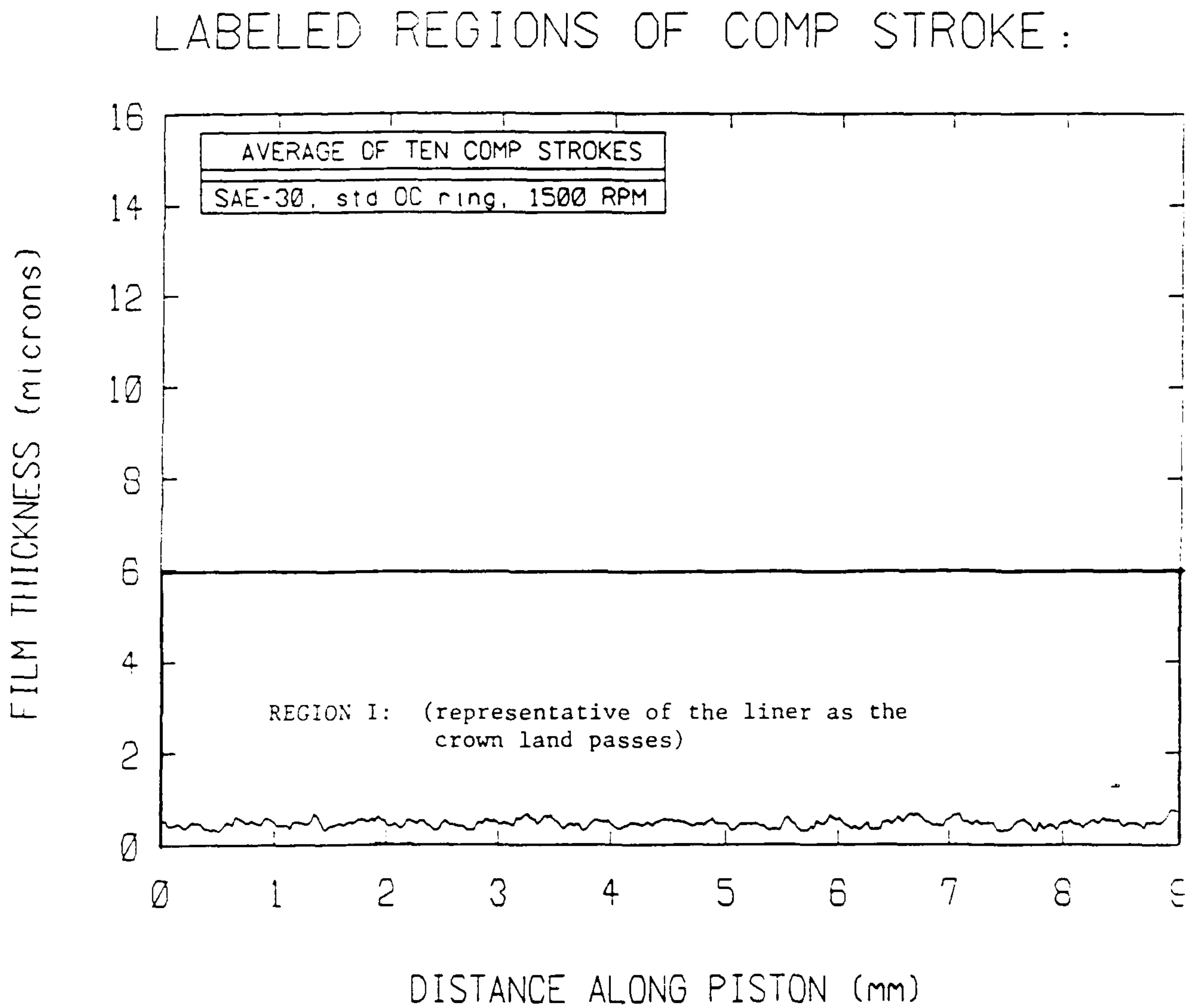

LABELED REGIONS OF COMP STROKE:
AVERAGE OF TEN COMP STROKES
SAE-30, std OC ring, 1500 RPM
REGION I: (representative of the liner as the crown land passes)
FILM THICKNESS (microns)
DISTANCE ALONG PISTON (mm)
0
2
4
6
8
10
12
14
16
1
3
5
7
9

Figure 15

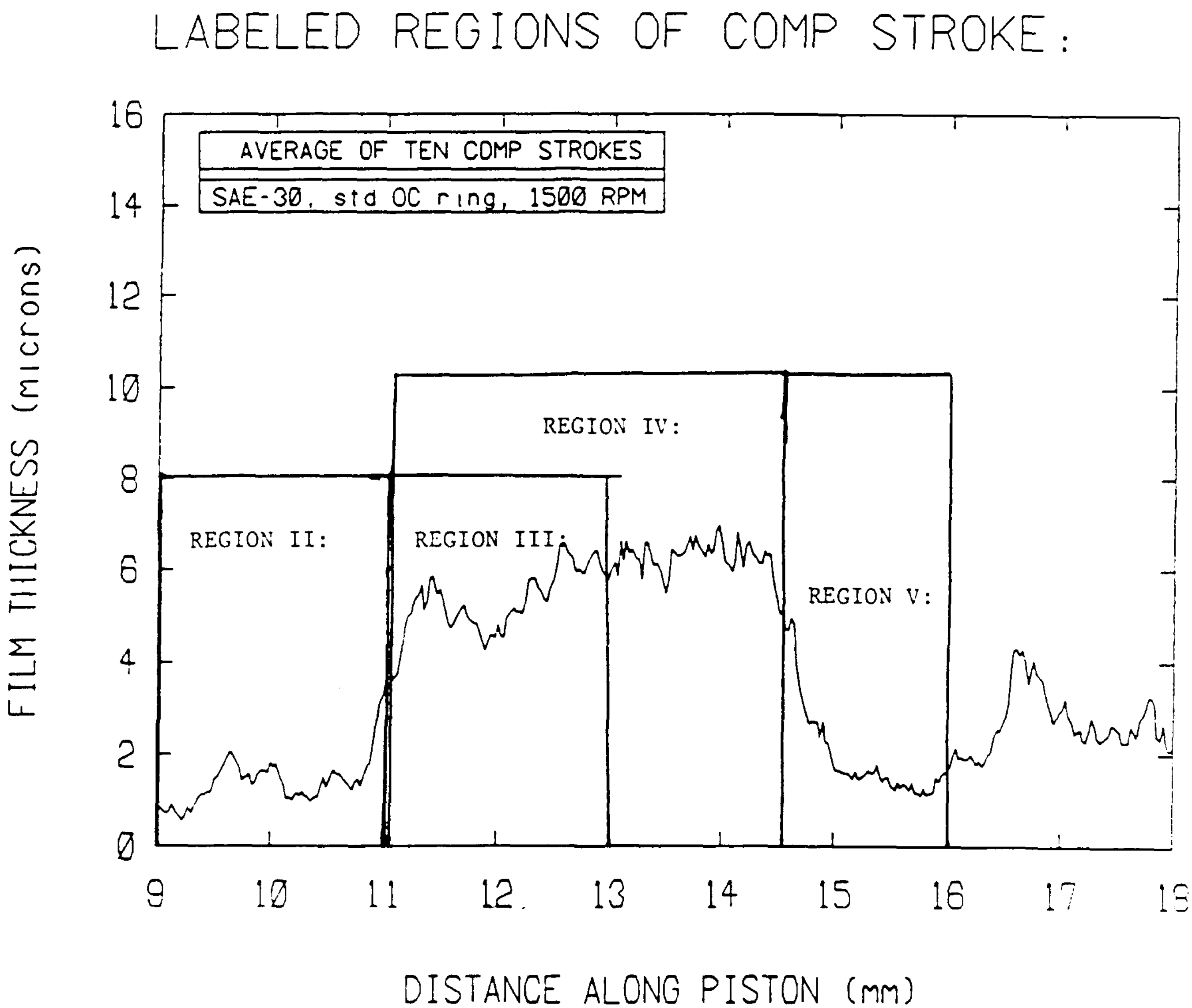

LABELED REGIONS OF COMP STROKE:
AVERAGE OF TEN COMP STROKES
SAE-30, std OC ring, 1500 RPM
REGION II:
REGION III:
REGION IV:
REGION V:
FILM THICKNESS (microns)
DISTANCE ALONG PISTON (mm)
16
14
12
10
8
6
4
2
0
9
10
11
12
13
14
15
16
17
18

Figure 16

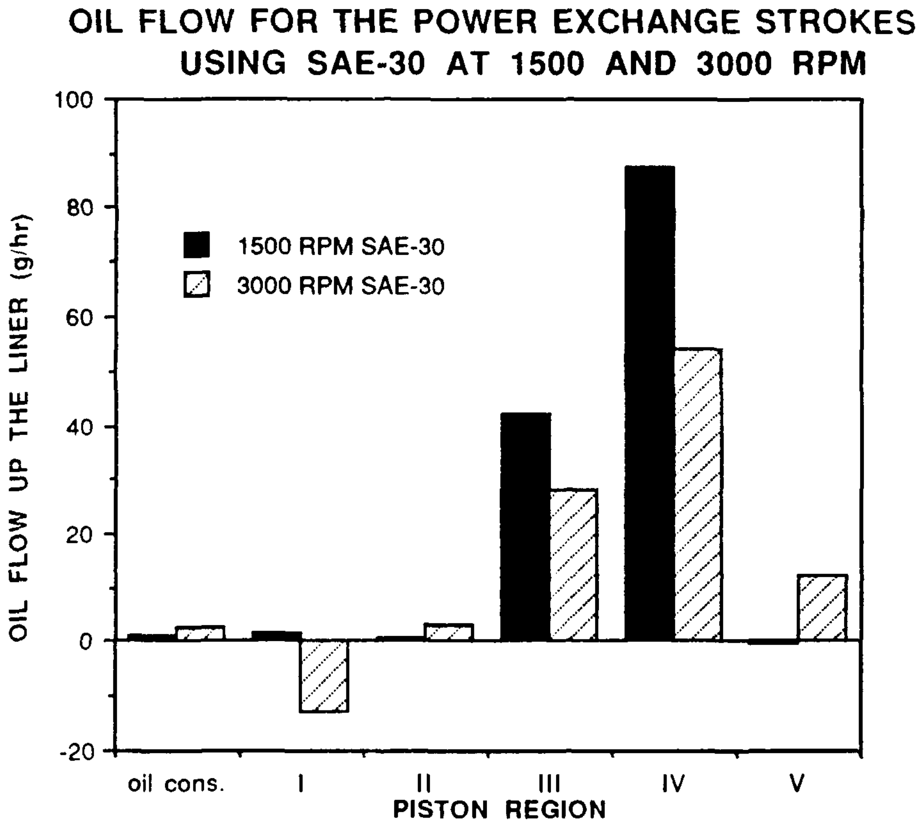

OIL FLOW FOR THE POWER EXCHANGE STROKES
USING SAE-30 AT 1500 AND 3000 RPM
OIL FLOW UP THE LINER (g/hr)
100
80
60
40
20
0
-20
1500 RPM SAE-30
3000 RPM SAE-30
oil cons.
I
II
III
IV
V
PISTON REGION

Figure 17

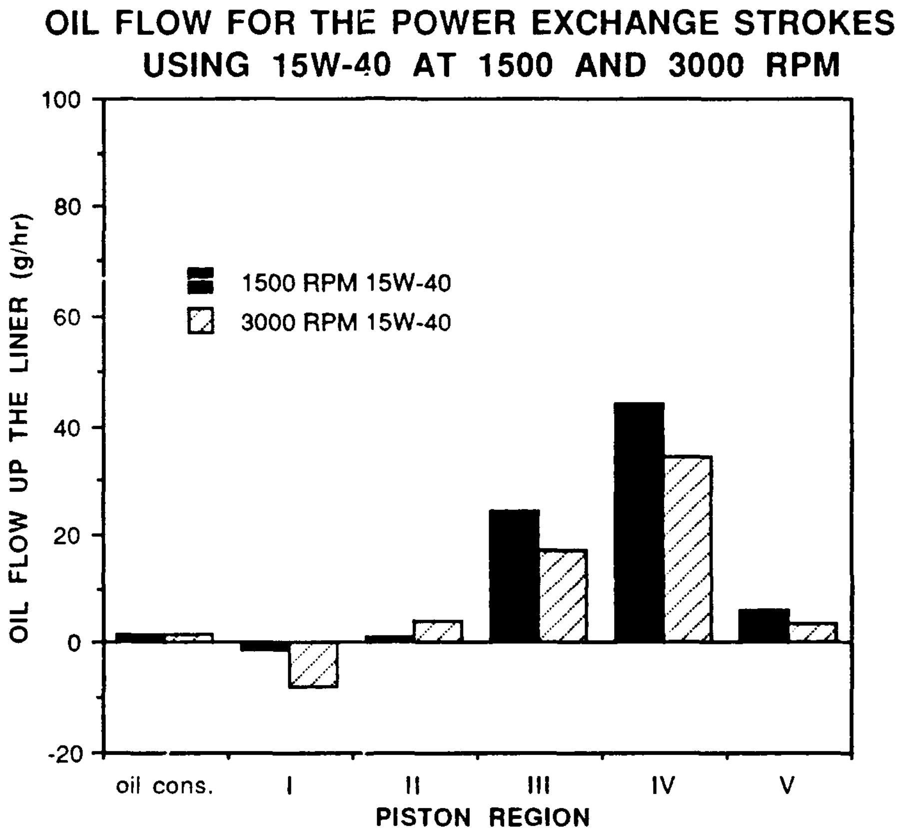

OIL FLOW FOR THE POWER EXCHANGE STROKES
USING 15W-40 AT 1500 AND 3000 RPM
OIL FLOW UP THE LINER (g/hr)
100
80
60
40
20
0
-20
1500 RPM 15W-40
3000 RPM 15W-40
oil cons.
I
II
III
IV
V
PISTON REGION

Figure 18

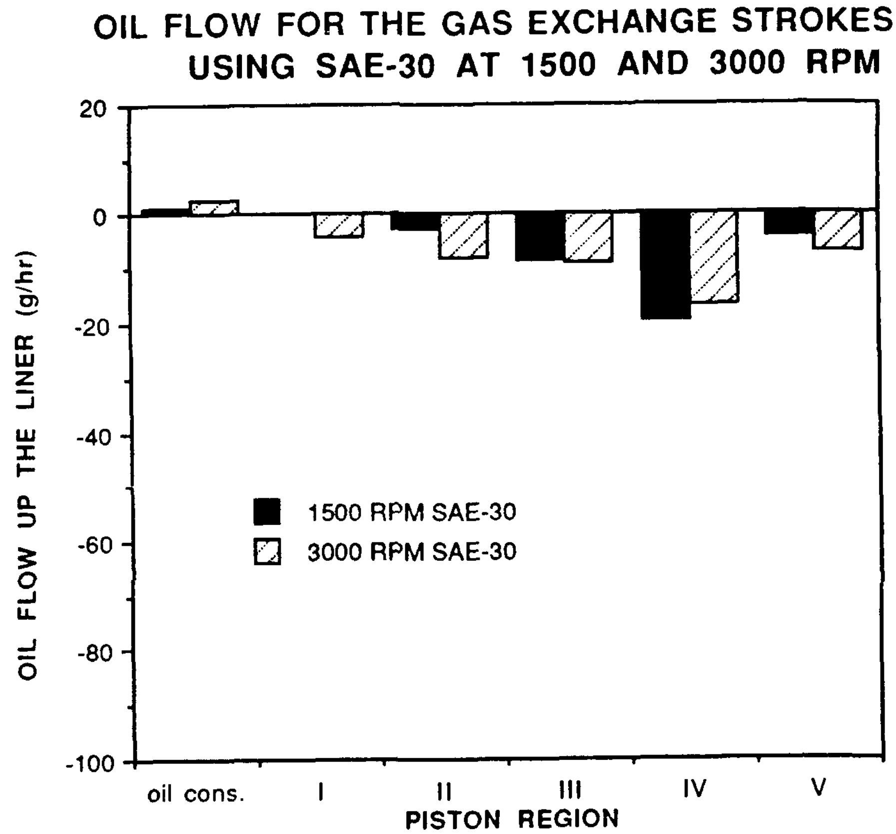
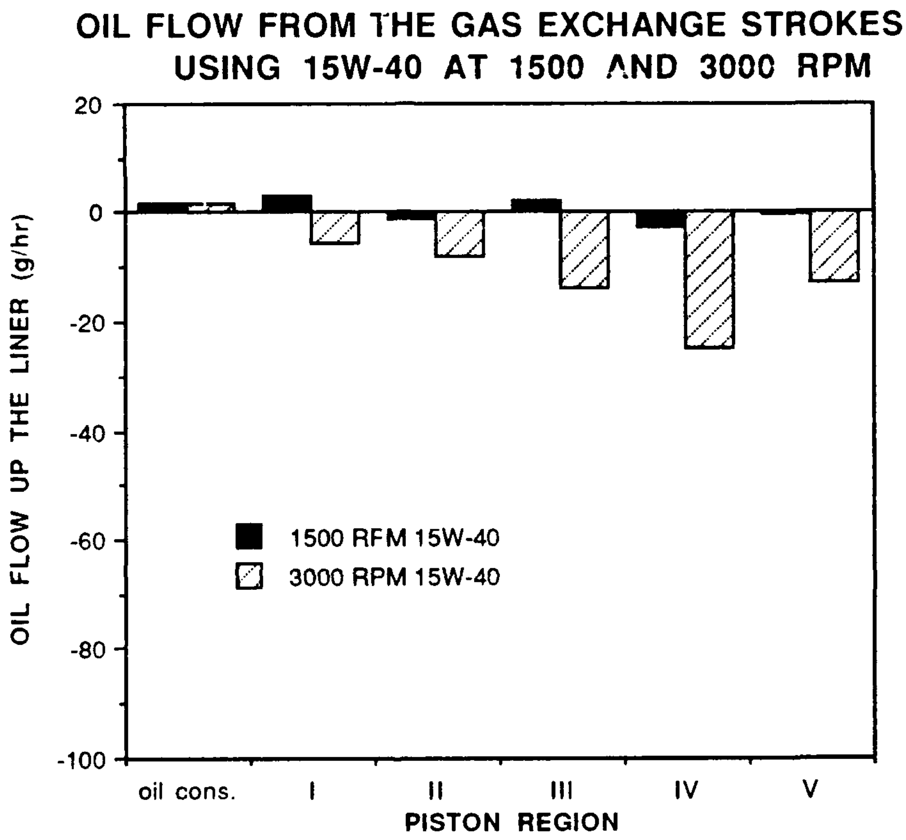

OIL FLOW FOR THE GAS EXCHANGE STROKES
USING SAE-30 AT 1500 AND 3000 RPM
OIL FLOW UP THE LINER (g/hr)
20
0
-20
-40
-60
-80
-100
1500 RPM SAE-30
3000 RPM SAE-30
oil cons.
I
II
III
IV
V
PISTON REGION

Figure 19



OIL FLOW FROM THE GAS EXCHANGE STROKES
USING 15W-40 AT 1500 AND 3000 RPM
OIL FLOW UP THE LINER (g/hr)
20
0
-20
-40
-60
-80
-100
1500 RFM 15W-40
3000 RPM 15W-40
oil cons.
I
II
III
IV
V
PISTON REGION


Figure 20

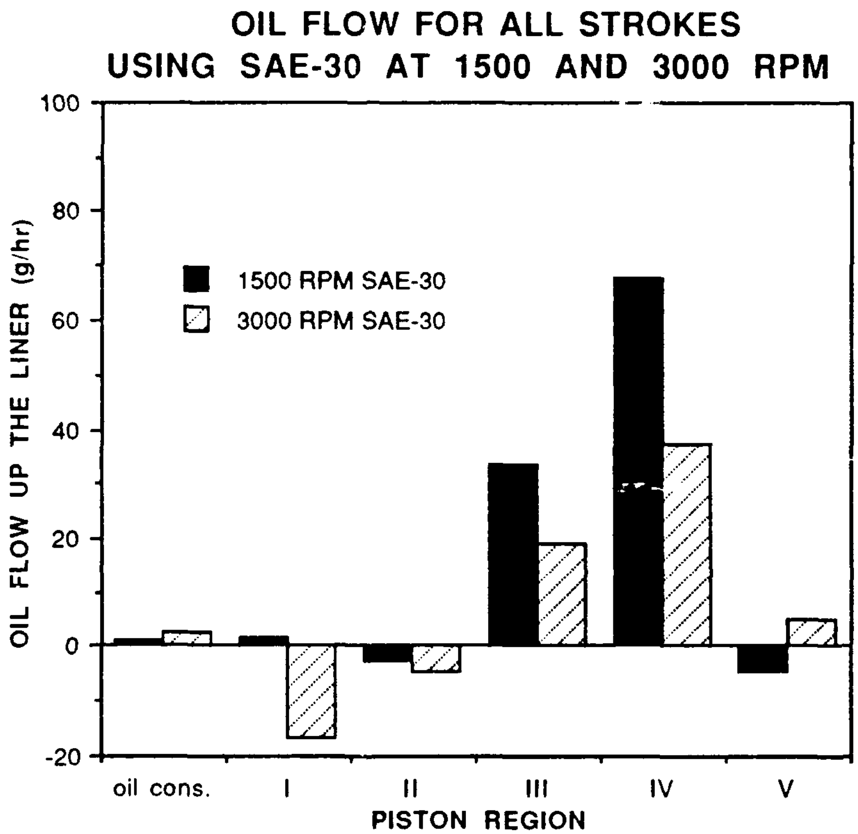

OIL FLOW FOR ALL STROKES
USING SAE-30 AT 1500 AND 3000 RPM
100
80
60
40
20
0
-20
OIL FLOW UP THE LINER (g/hr)
1500 RPM SAE-30
3000 RPM SAE-30
oil cons.
I
II
III
IV
V
PISTON REGION

Figure 21

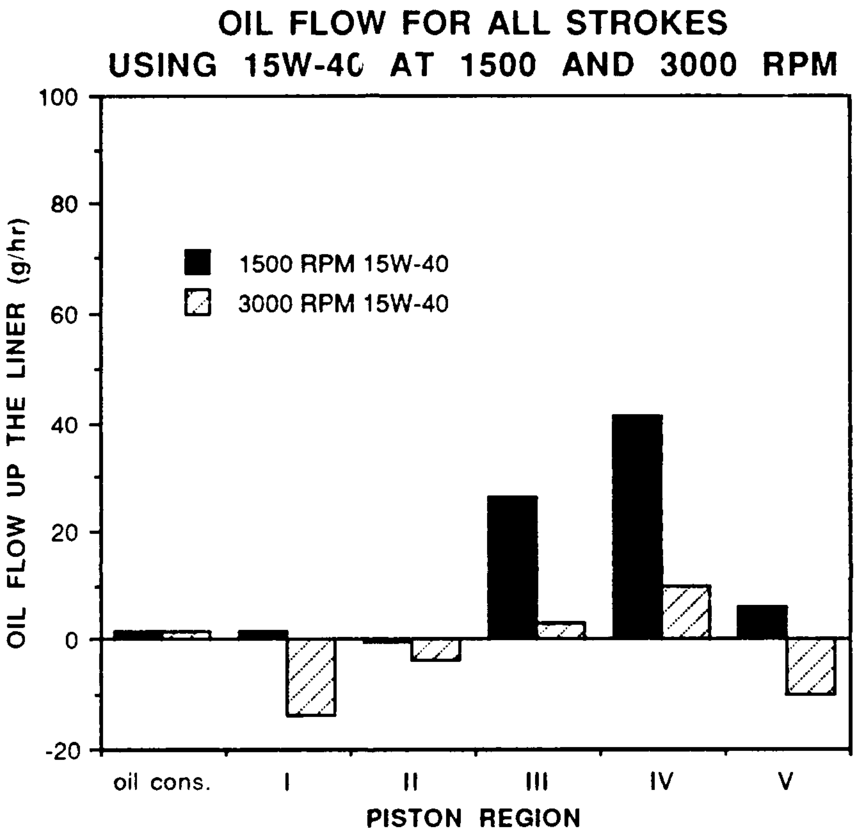

OIL FLOW FOR ALL STROKES
USING 15W-40 AT 1500 AND 3000 RPM
100
80
60
40
20
0
-20
OIL FLOW UP THE LINER (g/hr)
1500 RPM 15W-40
3000 RPM 15W-40
oil cons.
I
II
III
IV
V
PISTON REGION

Figure 22

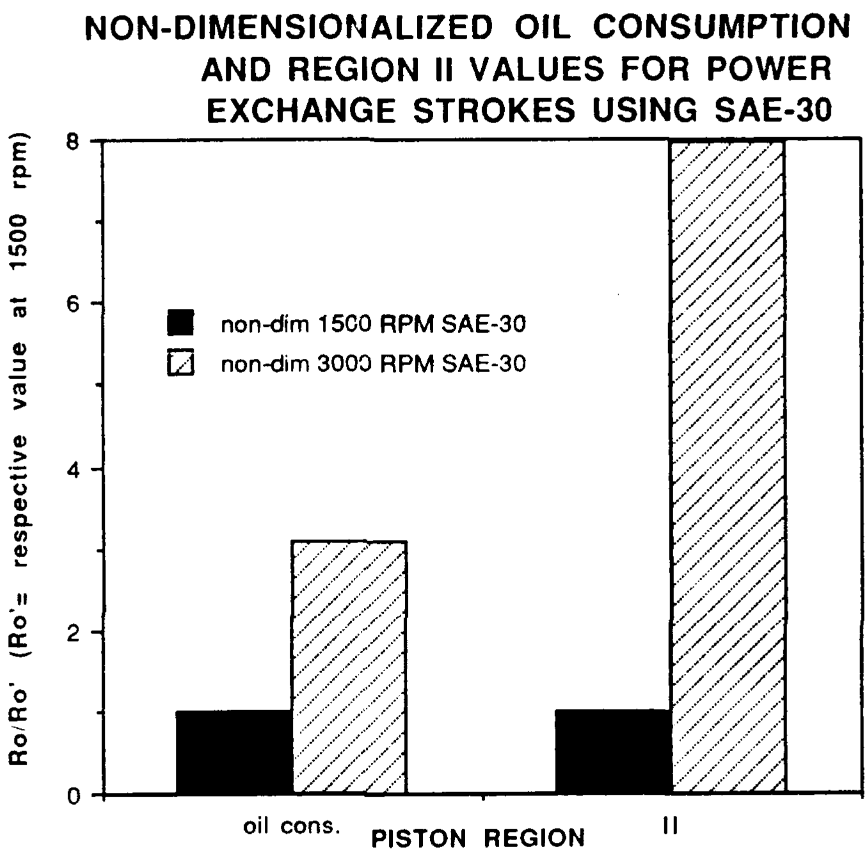

NON-DIMENSIONALIZED OIL CONSUMPTION
AND REGION II VALUES FOR POWER
EXCHANGE STROKES USING SAE-30
Ro/Ro' (Ro'= respective value at 1500 rpm)
0
2
4
6
8
non-dim 1500 RPM SAE-30
non-dim 3000 RPM SAE-30
oil cons.
PISTON REGION
II

Figure 23

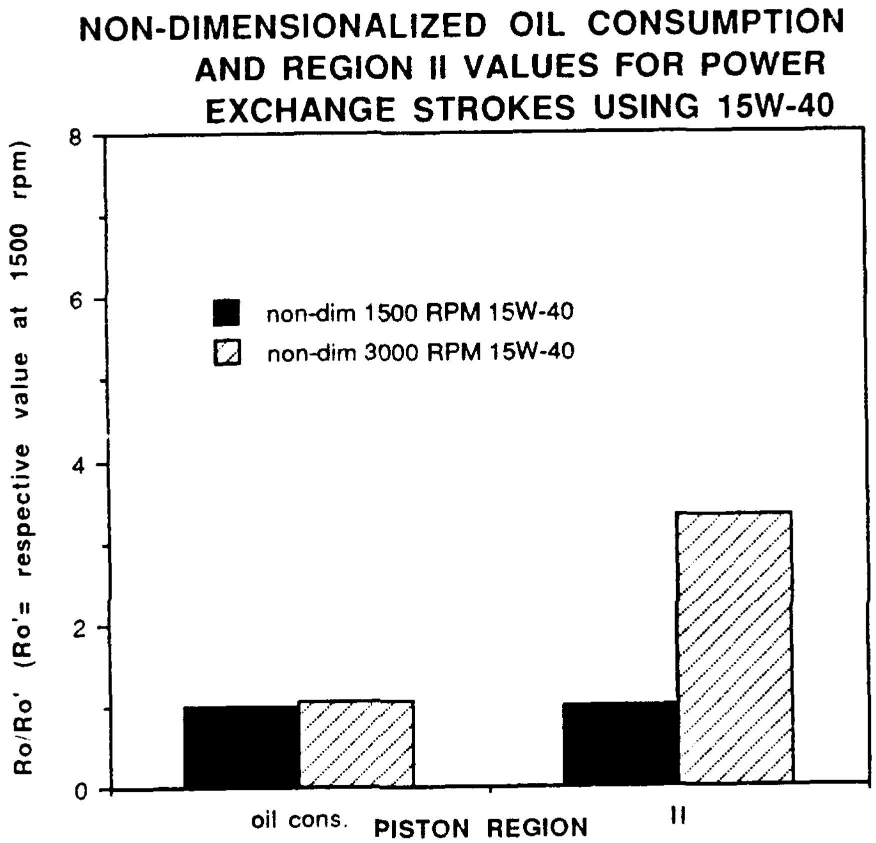

NON-DIMENSIONALIZED OIL CONSUMPTION
AND REGION II VALUES FOR POWER
EXCHANGE STROKES USING 15W-40
Ro/Ro' (Ro'= respective value at 1500 rpm)
8
6
4
2
0
non-dim 1500 RPM 15W-40
non-dim 3000 RPM 15W-40
oil cons.
PISTON REGION
II

Figure 24

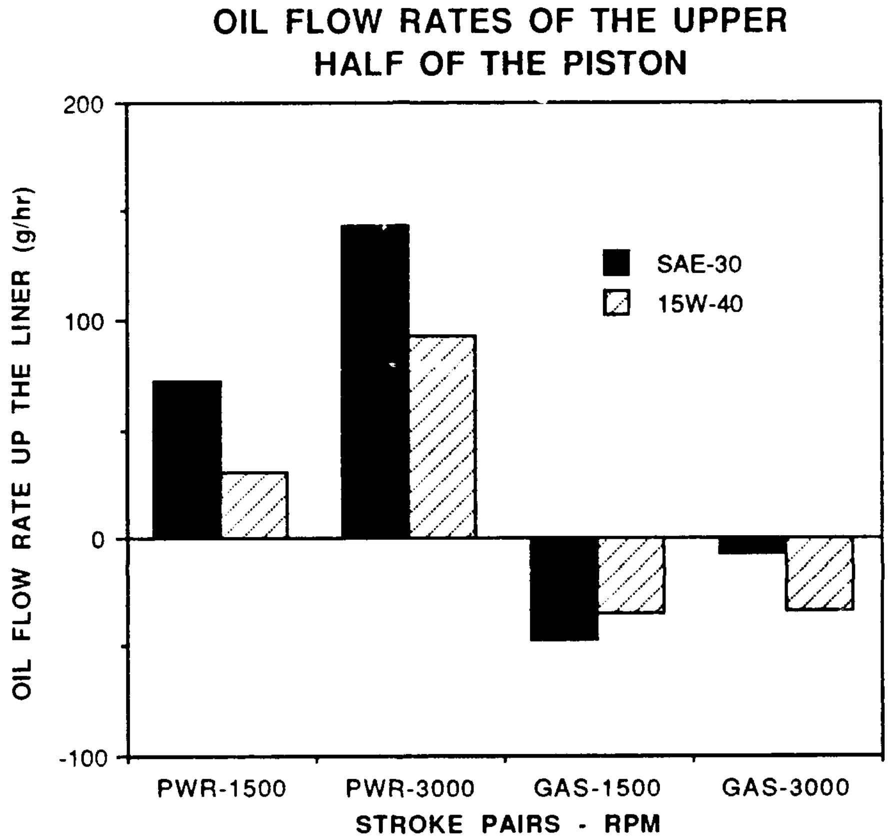

OIL FLOW RATES OF THE UPPER
HALF OF THE PISTON
OIL FLOW RATE UP THE LINER (g/hr)
200
100
0
-100
SAE-30
15W-40
PWR-1500
PWR-3000
GAS-1500
GAS-3000
STROKE PAIRS - RPM

Figure 25

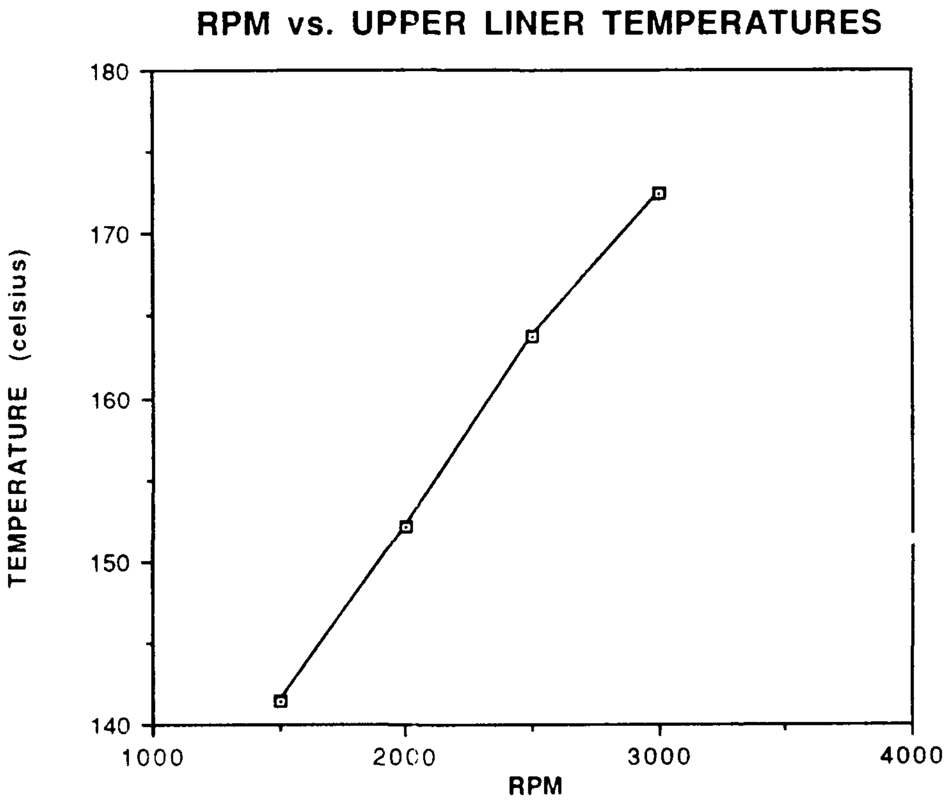

RPM vs. UPPER LINER TEMPERATURES
TEMPERATURE (celsius)
180
170
160
150
140
1000
2000
3000
4000
RPM

Figure 26

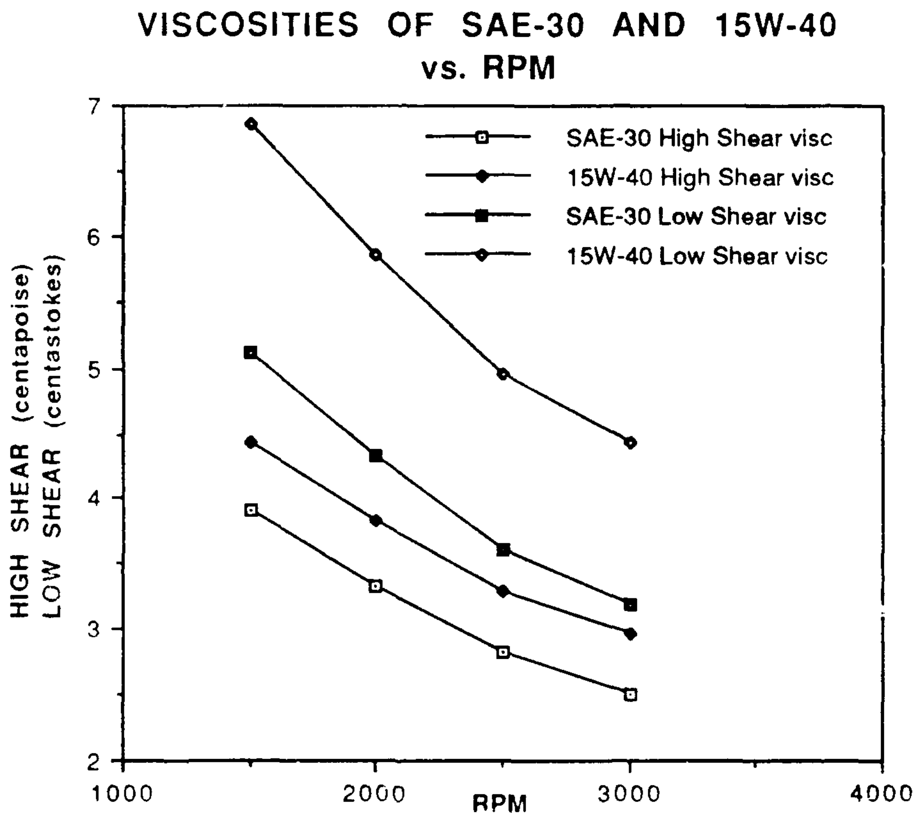

VISCOSITIES OF SAE-30 AND 15W-40
vs. RPM
SAE-30 High Shear visc
15W-40 High Shear visc
SAE-30 Low Shear visc
15W-40 Low Shear visc
HIGH SHEAR (centapoise)
LOW SHEAR (centastokes)
7
6
5
4
3
2
1000
2000
RPM
3000
4000

Figure 27

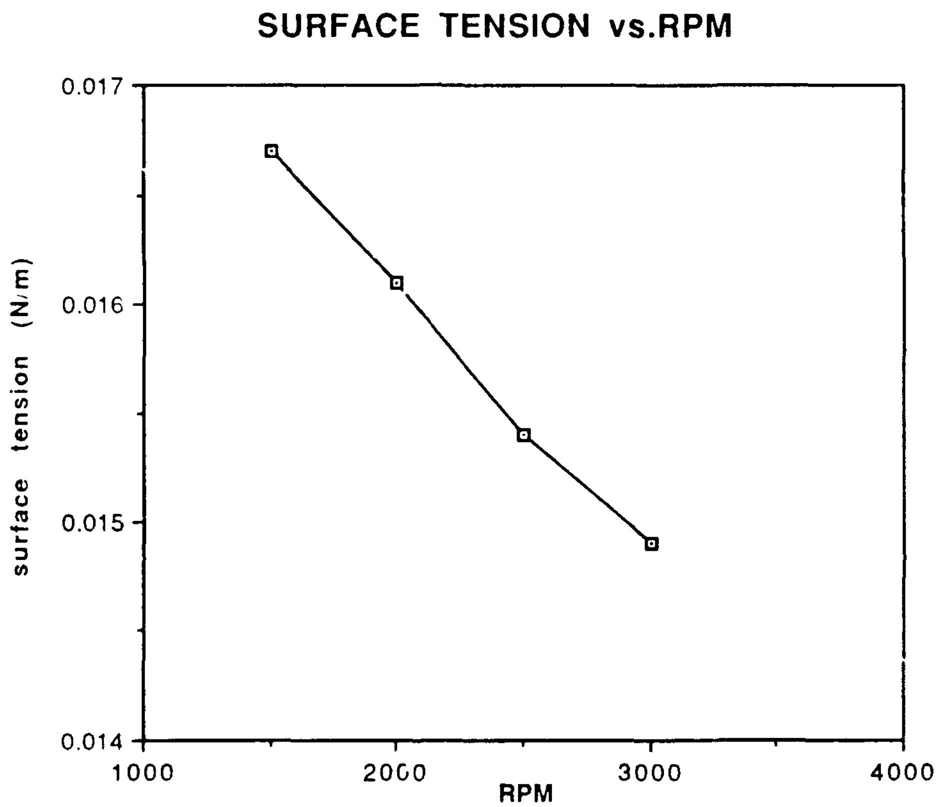

SURFACE TENSION vs.RPM
0.017
0.016
0.015
0.014
surface tension (N/m)
1000
2000
3000
4000
RPM

Figure 28

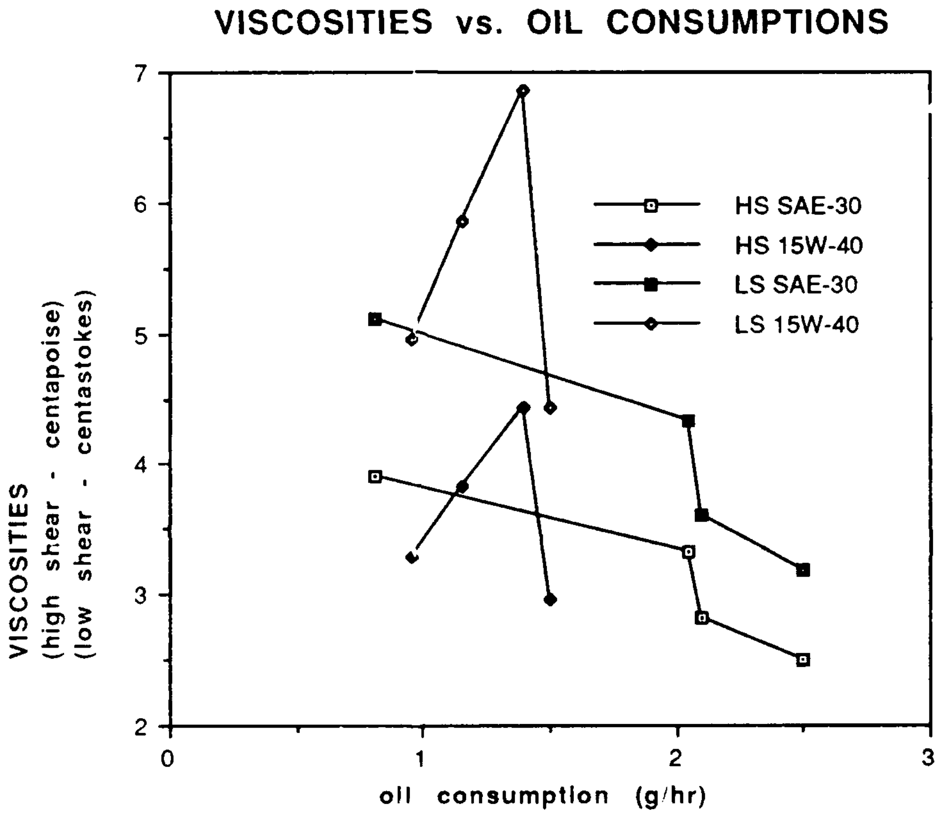

VISCOSITIES vs. OIL CONSUMPTIONS
7
6
5
4
3
2
0
1
2
3
VISCOSITIES
(high shear - centapoise)
(low shear - centastokes)
oil consumption (g/hr)
HS SAE-30
HS 15W-40
LS SAE-30
LS 15W-40

Figure 29